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Hardware-in-the-Loop Simulation to Evaluate the Performance and Constraints of the Red-light Violation Warning Application on Arterial Roads

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HARDWARE-IN-THE-LOOP SIMULATION TO EVALUATE THE PERFORMANCE AND CONSTRAINTS OF THE RED-LIGHT VIOLATION WARNING APPLICATION ON ARTERIAL ROADS

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Mahmoud Arafat Sadek Helal

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To: Dean John L. Volakis
College of Engineering and Computing

This dissertation, written by Mahmoud Arafat Sadek Helal, and entitled Hardware-in-the-Loop Simulation to Evaluate the Performance and Constraints of the Red-light Violation Warning Application on Arterial Roads, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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Florida International University, 2022

DEDICATION

I dedicate this dissertation to my mom, Zeinab El-Haggar,

who fills my life with love, smiles, and support.

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ABSTRACT OF THE DISSERTATION

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Understanding the safety and mobility impacts of Connected Vehicle (CV) applications is critical for ensuring effective implementations of these applications. This dissertation provides an assessment of the safety and mobility impacts of the Red-Light Violation Warning (RLVW), a CV-based application at signalized intersections, under pre-timed signal control and semi-actuated signal control utilizing Emulator-in-the-loop (EILS), Software-in-the-loop (SILS), and Hardware-in-the-loop simulation (HILS) environments. Modern actuated traffic signal controllers contain several features with which controllers can provide varying green intervals for actuated phases, skip phases, and terminate phases depending on the traffic demand fluctuation from cycle to cycle. With actuated traffic signal operations, there is uncertainty in the end-of-green information provided to the vehicles using CV messages. The RLVW application lacks accurate input information about when exactly a phase is going to be terminated since this termination occurs when a gap of a particular length is encountered at the detector. This study compares

the results obtained with the use of these three aforementioned simulation platforms and how the use of the platforms impacts the assessed performance of the modeled CV application. In addition, the study investigates using HILS and a method to provide an Assured Green Period (AGP) which is a definitive time when the green interval will end to mitigate the uncertainties associated with the green termination and to improve the performance of the CV application.

The study results showed that in the case of pre-timed signal control, there are small differences in the assessed performance when using the three simulated platforms. However, in the case of the actuated control, the utilization of EILS showed significantly different results compared to the utilization of the SILS and the HILS platforms. The use of the SILS and the HILS platforms produced similar results. The differences can be attributed to the variations in the time lag between vehicle detection and the use of this information between the EILS and the other two platforms. In addition, the results showed that the reduction in red-light running due to RLVW was significantly higher with pre-timed control compared to the reduction with semi-actuated control. The reason is the uncertainty in the end-of-green intervals provided in the messages communicated to the vehicles, as stated above. In the case of semi-actuated control, the results showed that the safety benefits of the RLVW without the use of AGP were limited. On the other hand, the study results showed that by introducing the AGP, the RLVW can reduce the number of red-light running events at signalized intersections by approximately 92% with RLVW utilization of 100%. However, the results show that the application of the AGP, as applied and assessed in this dissertation, can have increased stopped delay and approach delay under congested traffic conditions. This issue will need to be further investigated to determine the optimal setting of the AGP considering both mobility and safety impacts.

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ABBREVIATIONS AND ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AAW	Actuated Advance Warning
AGET	Assured Green End Time
AGP	Assured Green Period
API	Application Program Interface
ATC	Actuated Traffic Controller
BSM	Basic Safety Message
CACC	Cooperative Adaptive Cruise Control
CAV	Connected and Automated Vehicle
CCD	Critical-safe Crossing Distance
CCM	Controller Communication Module
CDA	Cooperative Driving Automation
CI	Connected Intersection
CIB	Controller Input Buffer
CID	Controller Interface Device
CMD	Windows Command Prompt
COM	Component Object Module
CV	Connected Vehicle
DII	Driver Infrastructure Interface
DVI	Driver Vehicle Interface
DSRC	Dedicated Short Range Communication
EILS	Emulator-in-the-loop Simulation

EVP	Emergency Vehicle Preemption
FHWA	Federal Highway Administration
FIU	Florida International University
GLOSA	Green Light Optimized Speed Advisory
GPS	Global Positioning System
GRG	Generalized Reduced Gradient
HIL	Hardware in the Loop
HILS	Hardware in the Loop Simulation
ITE	Institute of Transportation Engineers
JPO	Joint Program Office
LCTR	Lehman Center for Transportation Research
MPH	Mile Per Hour
NEMA	National Electrical Manufacturers Association
NHTSA	National Highway Traffic Safety Administration
NLP	Non-Linear Programming
NTCIP	National Transportation Communications for ITS protocol
OBE	On-board Equipment
OID	Object Identifier
PC	Personal Computer
PET	Post Encroachment Time
PRT	Perception Reaction Time
Q-SAID	Queue-aware Signalized Intersection Approach and Departure
RAM	Random Access Memory

RBC	Ring Barrier Controller
RLR	Red-Light Running
RLVW	Red-light Violation Warning
RMSE	Root Mean Squared Error
RS	Recommended Standard
RSE	Roadside Equipment
RSP	Roadside Processors
SAE	Society of Automotive Engineers
SDLC	Synchronous Data Link Control
SILS	Software-in-the-loop Simulation
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
SSAM	Surrogate Safety Assessment Model
SSD	Stop Sight Distance
SSE	SUM Squared Error
SSM	Surrogate Safety Measures
SUMO	Simulation of Urban Mobility
TCP	Transmission Control Protocol
TraCI	Traffic Control Interface
TTC	Time-to-collision
USDOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

V2X	Vehicle-to-Everything
VCID	Virtual Controller Interface Device
VCM	VISSIM Communication Module
VIL	Vehicle-in-the-Loop
VISSIM	PTV's Verkehr In Städten SIMulationsmodell

CHAPTER 1
INTRODUCTION

1.1 Background

The emergence of connected vehicle (CV) technologies in recent years has paved the road to new cutting-edge applications that are expected to result in transformative improvements in the performance of the transportation system. These applications promise the enhancement of safety and mobility while reducing the transportation environmental impacts. A fundamental prerequisite for CV applications to deliver the needed functionality at signalized intersections is the access to the signal phase and timing (SPaT) information in the traffic signal controller. Modern actuated traffic signal controllers contain several features with which controllers can provide varying green intervals for actuated phases, skip phases, and terminate phases depending on the traffic demand fluctuation from cycle to cycle. Such features introduce additional challenges when testing and evaluating the CV applications that are mainly based on the accuracy of the available signal information such as the current phase termination time due to the uncertainty in this information. The uncertainty in the SPaT messages with the presence of an actuated traffic signal controller is one of the main challenges that signalized intersection CV-based applications encounter.

Microscopic traffic simulation is widely used for simulating and testing emerging vehicle technologies in a risk-free controlled environment. Signal control and CV technologies and applications at signalized intersections can be simulated and tested using simulation platforms in three distinguishing approaches: Emulator-in-the-loop (EILS), Software-in-the-loop (SILS), and Hardware-in-the-loop (HILS). The results from simulation models of traffic signal controller operations are expected to be affected by the traffic signal control modeling and the latency between the vehicle detection and the use of the detection in traffic control when using the three platforms.

EILS is the simplest approach among the three approaches mentioned above and is the commonly used method for signal state generation both in practice and research of traffic simulation. As an example, the simulation software packages such as PTV's Verkehr In Städten SIMulationsmodell (VISSIM) generate the signal state using the built-in Ring Barrier Controller (RBC) logic programmed (PTV Group, 2020). SILS represents the incorporation of the commercial traffic signal controller functionalities and parameters into the software that usually resides on the computer that hosts the simulation software, providing the same functionalities as a physical controller. HILS incorporates a physical traffic signal controller in the loop to be used for generating signal states during simulation.

In addition to the potential differences in traffic signal operations that can impact the results of the simulation model, the use of different approaches to emulate signal control can impact the assessment of CV-based applications at signalized intersections. HILS is ideal for testing Connected Vehicle-to-Infrastructure (V2I) safety and mobility applications at signalized intersections. This is because it provides the ability to test the interfaces between the traffic controllers and roadside unit (RSU) and between the RSU and the on-board unit (OBU) using interface standards such as the National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) and the Society of Automotive Engineers (SAE) J2735 and J2945 standards. Such an environment can also assist in examining the impacts of V2I applications and the parameters associated with these applications and the signal controller on traffic operation performance. For example, V2I traffic safety applications such as red-light violation warning (RLVW) require the transmission of wireless messages from the RSU to the OBU that includes SPaT information obtained through an interface between the RSU and the traffic signal controller. When using the three different signal control approaches in the microscopic simulation of such applications, there is a potential for differences in the signal control timing that can affect the overall performance of the applications.

1.2 Problem Statement

Actuated signals consist of variable phases that are called and extended in response to traffic demands. With actuated traffic signal operations, there is uncertainty in the end-of-green information provided to the vehicles using the SPaT message. For this reason, as an example of CV-based applications, the RLVW application lacks accurate input information about when exactly the phase is going to be terminated since this termination occurs when a gap of a particular length is encountered at the detector. In the case of congested conditions on all movements, all phases are expected to reach their maximum values (Max Out) allowing the provision of accurate SPaT messages. The underlying algorithm on the On-Board Equipment (OBE) on the connected vehicles can then use this information to perform the required calculations and send alerts and warnings to drivers based on the received SPaT information. In the case of Cooperative Driving Automation (CDA), connected automated vehicles can use this information in planning their trajectories. However, in the case of less congested traffic operations, the signal phases are expected to terminate before the maximum green time is reached (Gap Out), which results in varying ends of the green time between cycles and affects the functionality and performance of the applications.

Previous research studies have evaluated the impacts of CV-based applications. However, there is a gap in the literature when it comes to assessing the benefits of CV-based applications at signalized intersections under actuated and semi-actuated signal controller operations. Moreover, researchers are using EILS, SILS, and HILS platforms to model CV applications and strategies (Bachuwar et al., 2020; Szendrei et al., 2018; Arafat et al., 2021; Zulkefli et al., 2018; Ma et al., 2018), although most research and industry projects use EILS. It is still not clear to what extent the utilization of different approaches to emulate signal control can affect the assessment of the performance of CV applications using simulation.

With this recognition, the main goal of this dissertation is to evaluate the performance of the RLVW as an example of CV-based applications under pre-timed signal controller and semi-actuated signal controller and to assess a method to mitigate the uncertainty mentioned above. In addition, this dissertation performs a cross-evaluation between the use of the aforementioned approaches in simulating signal control to quantify the impacts on the results of the assessment of RLVW, as an example of CV-based applications under two different modes of signal control (i.e., pre-timed and semi-actuated control). This evaluation will answer the question of whether the simulation of identical signalized intersections with identical signal timing plans and traffic flow would generate similar results when assessing the RLVW application with EILS, SILS, and HILS in terms of the number of red-light running and the overall safety of the intersection.

The microscopic simulation environments EILS, SILS, and HILS are utilized in this dissertation for assessing the impacts of the RLVW application. However, the HILS is used as the primary tool to investigate a proposed solution that mitigates the uncertainties associated with the green interval termination. The utilized simulation environment allows the interface of the simulation software and hardware elements in a hardware-in-the-loop simulation (HILS) platform. The platform integrates a physical actuated traffic signal controller for better evaluation of the performance of the RLVW application. The study uses the direct output files from the simulation to analyze the mobility benefits of the application. In addition, the study used the simulated vehicle trajectories to identify, classify, and evaluate the safety benefits of the application based on surrogate safety measures utilizing the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration (FHWA, 2008).

1.3 Research Goal and Objectives

This research assesses the performance of CV-based RLVW under pre-timed signal control and semi-actuated signal control by developing EILS, SILS, and HILS environments and methods for testing and evaluating the application. The HILS incorporates a microscopic simulation tool and traffic signal controller to evaluate the RLVW in a CV environment. The specific objectives are:

1. Develop a HILS platform and methods for simulating the CV-based RLVW that have the potential of integrating signal control and CV system hardware components and simulation in a laboratory environment.
2. Assess the impact of semi-actuated signal control on the performance of RLVW application compared to pre-timed signal control.
3. Provide a solution to mitigate the uncertainties associated with the green interval termination and improve the performance of the CV-based RLVW application.

1.4 Dissertation Organization

This dissertation is comprised of five chapters. Chapter 2 presents a comprehensive literature review of the state-of-the-art microscopic simulation and calibration of CV-based V2I applications. In addition, the literature includes a review of HILS platforms for testing CV-based V2I applications. Chapter 3 presents the methodology that is used to achieve the stated objectives and overviews the description of the proposed HILS framework. Chapter 4 describes results from the application of the methodology developed in this study. Chapter 5 concludes this dissertation by summarizing the contributions of this research and providing recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

There are several parameters related to the CV-based RLVW control algorithm and the actual traffic signal controller that are difficult to be tested or evaluated using the microscopic simulation tool by itself. However, the recent advancement in simulation packages and the advanced signal controller Application Program Interfaces (APIs) provide researchers with a wide variety of options to test and evaluate the impacts of CV-based technologies in a realistic and risk-free environment. HILS is one of the available options that allow better replication of real-world operations in the modeling of CV applications. This chapter provides a comprehensive literature review on three main topics: (a) utilizing microscopic simulation and simulators in modeling CV-based RLVW applications; (b) modeling the driver's behavior and the probability of driver's stopping on amber; and (c) review of studies that utilized EILS, SILS, and HILS to model CV applications. Section 2.1 focuses on the CV-based V2I RLVW application algorithms available in the academic literature. Section 2.2 presents an overview of the available models that replicate the driver's behavior in the dilemma zone and the probability of the driver's stopping on amber. Finally, the existing literature related to the EILS, SILS, and HILS platforms and system components is presented in section 2.3.

2.1 Red-Light Violation Warning Application

This section reviews different CV-based RLVW applications. It is divided into three broad sub-sections: (a) the description of the RLVW; (b) the safety impacts of the RLVW application; and (c) the evaluation and assessment of the RLVW application.

2.1.1 Description of the RLVW

According to the Traffic Signal Timing Manual published by the Transportation Research Board (Urbanik et al., 2015), there are two rules of traffic signals operation pertaining to the entry of drivers into a signalized intersection on the yellow interval. These two rules can be classified as permissive yellow entry and restrictive yellow entry. With permissive yellow rule operation, vehicles are allowed to enter the intersection during the entire yellow interval and a signal violation occurs if the vehicle crosses the downstream stop bar after the onset of red. On the other hand, the yellow interval can be timed and designed according to a restrictive yellow rule operation. Under the restrictive yellow rule, vehicles can neither enter nor be in the intersection on red. A jurisdiction having the restrictive yellow rule can cite a driver running a yellow light as if the vehicle has not cleared the intersection after the onset of red. The permissive yellow rule has been widely adopted in the design and timing of traffic signals in thirty-seven states as an effective solution to increase the capacity of through-lanes and thus reduce delays at signalized intersections. However, this permissive rule can increase another type of violation commonly known as the red-light running (RLR) violation. Florida is one of the thirty-seven states that have adopted the permissive yellow rule of traffic signals operation. The permissive yellow rule definition is applied and used in this dissertation.

RLVW is a CV-based safety application that aims to reduce the number of red-light running events and improve safety at signalized intersections. RLVW is expected to reduce the uncertainty in the driver’s behavior, particularly in the vicinity of the dilemma zone due to increasing drivers’ awareness of the signal status as they approach a signalized intersection (Stephens et al., 2015). A key element that pertains to the success of this application is the presence of roadside equipment (RSE) that transmits SPaT information from the traffic signal controller to the CV-equipped vehicles. The RLVW application on the OBE utilizes this information along with the vehicle approaching speed and distance to the intersection stop line to provide warnings to drivers, allowing them to make decisions to avoid running a red-light (Stephens et al., 2012). The application can also work as part of cooperative driving automation with the utilization of the SPaT information by the vehicle automation software.

The RLVW can utilize two decision support interface alternatives, Driver Infrastructure Interface (DII) and Driver Vehicle Interface (DVI). Neale et al., (2007) tested the two types of interfaces to determine which one was most effective and allowed drivers to make the right decision and the correct response of braking by the intersection stop bar. The study results showed that DVIs are more effective in sending violation warnings than DIIs. In addition, the results showed that combining a vehicle's enhanced braking capability with a DVI warning enhanced the range of acceptable DVIs.

An ongoing effort funded by the United States Department of Transportation (USDOT) ITS Joint Program Office (JPO), referred to as the Connected Intersection (CI) project, has defined the concept of operations, functional requirements, system design details, and testing requirements for the CV-based RLVW applications (ITE CI committee, 2021). There are no official documents from this effort yet, but such documents are expected to be released in the near future. The above-mentioned USDOT effort identified the need for what it called an assured green period (AGP) to mitigate the issue with the uncertainty in the provision of the end of the green time in SPaT messages with actuated signal control. The AGP is a definitive time when the green interval will end to mitigate the uncertainties associated with the green termination and to improve the performance of the CV application. This definitive green is provided for the phase that serves the approaching CV vehicles and is calculated based on the approach speed and distance from the stop line. When the AGP is combined with the yellow interval and all-red interval, it provides enough time for reducing the possibility that an equipped vehicle will violate the red-light and continue to be present in the intersection during a red signal state.

2.1.2 Safety Impacts of the RLVW Application

Stephens et al., (2015) described the impacts of the deployment of RLVW V2I safety application. These impacts are summarized as follows:

- Real-Time Messaging: The greatest impact is that drivers will receive real-time advisories, alerts, and warnings while driving based on their current driving conditions.
- Reduction in Red-Light Running Incidents: The RLVW application will reduce the number of vehicles exposed to cross-traffic due to intersection violations, resulting in fewer collisions between red-light violators and cross-traffic.
- Effective Warning: The RLVW is designed to provide drivers with a combination of haptic, visual, and/or audio warnings in an effective format that does not distract or overwhelm them. These warnings are designed to be presented to drivers in a timeframe that provides adequate reaction time to reduce speed and safely stop at the intersection stop bar before illegally entering the intersection.
- Modified Driving Behavior: It is expected that drivers will modify their driving behaviors in response to the RLVW messages, thus creating a safer driving environment.

2.1.3 Assessments of the RLVW Application

Studies have relied on field observations or driving simulators when assessing the effects of RLVW (Neale et at., 2006; Yang and Najm 2007; Zhang et al., 2021; Moon and Park 2010; Roglinger and Facchi 2011; Xiang et al., 2016; and Jang et al., 2011). Banerjee et al. (2020) analyzed the effect of RLVW on drivers' braking behavior as reflected by the speed reduction time series at the onset of amber. For this purpose, the study used a driving simulator and eye-tracking device to observe the eye and head movement of the recruited participants. The simulation environment issued RLVW to the simulated vehicles crossing a defined point, 170 feet from the approach stop bar, when the vehicle crossed the defined point at a speed exceeding the limit of 30 mph, giving drivers enough time to come to a complete stop at the stop bar. The results showed that participants react more quickly to the change in traffic light in the presence of RLVW.

Nakamura et al., (2016) assessed the changes in drivers' behavior due to the presence of the V2I Red-light violation warning system that provides voice navigation using a driving simulator experiment. In the driving simulator, a voice warning was issued to the drivers approaching a signalized intersection allowing them to make the right decision to avoid running a red-light or a rear-end crash. The experiments were conducted on three different scenarios. The first scenario involved providing a voice warning at the right time, while the second scenario involved providing the information with a time lag. The third scenario was conducted with no information provided. The study results showed the presence of 24 incidents when no alerts were provided, while only four incidents of a deceleration of more than 5 m/s2 occurred when alerts were provided at the right time.

A field test was conducted by Park et al. (2013) to evaluate the use of the RLVW application, which relies on vehicle speed and location in the dilemma zone when activating the warning. The results from the testing showed a reduction in red-light violations and consequently intersection collisions.

Jang et al. (2011) developed a red-light violation warning that consists of a prediction model and a warning algorithm. The warning algorithm was based on the minimum safe stopping sight distance (SSD) and the critical safe crossing distance (CCD). The CCD indicates the existence of a dilemma and is a function of the duration of the amber phase, approaching vehicle speed, and driver's reaction time, among other parameters. If the SSD is greater than the CCD for a given vehicle, a dilemma exists. The prediction model used the remaining signal phase time to predict if there is a potential for a red-light violation based on the collected vehicle location and speed. The prediction model was tested using a microscopic simulation model. However, the calibration of the model utilized the typical parameters used in calibrating microscopic simulation models and did not calibrate the microscopic driver behaviors in the model considering the probability of stopping-on-amber that impacts the red-light running.

Yan et al. (2015) examined a prototype concept of an RLVW system that sends audio alerts to drivers approaching a signalized intersection at the onset of yellow. The researchers analyzed the effect of RLVW on the number of red-light running violations using a driving simulator and showed a reduction in the red-light running violations by 84.3 percent. In addition, the researchers reported that the RLVW reduces the drivers' likelihood to make go decisions at the onset of yellow 86 times compared to unequipped vehicles.

Nassereddine et al. (2021) conducted a driving simulator experiment to evaluate the benefits of a CV-based RLVW application that communicates in-vehicle alerts about the presence of a potential vehicle running the red-light. The experiments were conducted using three different scenarios where the RLVW system issued the alert at 50, 100, and 150 feet upstream of the stop line. The study results showed that the utilized warning system was more effective in sending violation warnings when activated at a distance of 50 feet or 100 feet upstream of the stop line.

Hussain et al. (2020) assessed the changes in drivers' safe-stopping behavior and red-light running voice warning alternatives using a driving simulator experiment. The experiments evaluated five different alternatives that include providing the default traffic signal setting, flashing green, red LED ground lights (R-LED), yellow interval countdown sign, and red-light running detection camera warning (RW-gantry). The study showed that the R-LED and the RW-gantry were the most effective solutions in encouraging a consistent stopping behavior at the signalized intersection.

Mohammed et al. (2016) tested the impact of providing in-vehicle advisory auditory RLVW. The researchers utilized a real-world testbed that is consisted of a physical traffic signal controller, roadside equipment, on-board equipment, and a testing vehicle. The drivers' performance was tested in terms of the average speed, maximum speed, and acceleration/deceleration profiles. The researchers reported that the proposed application has promising impacts on improving safety and driver awareness at signalized intersections.

2.2 Drivers' Behavior in Dilemma Zone

Since drivers' behavior in the dilemma zone contributes significantly to the frequency of RLR, such behavior must be accurately replicated in the simulation model used to evaluate RLVW applications. Several researchers utilized field tests and observations to study the distributions of the Stop and Go decisions and the resulting RLR events as a function of parameters, such as vehicle approach speed, distance to stop bar at the onset of amber, driver's age, and perception reaction time (PRT) among other parameters (Elmitiny et al., 2010; Rakha et al., 2007; Gates and Noyce, 2010; Hurwitz et al., 2012; Elhenawy et al., 2015; Van der Horst and Wilmink, 1986; and Sheffi and Mahmassani, 1981). Gates and Noyce (2007) proposed a logistic regression analysis to predict how likely a driver is to Stop or Go at different intervals of time to the stop bar at an urban intersection site. The authors showed that the model agrees well with previous models and can provide a reasonable prediction of drivers' behavior in the dilemma zone. This study used this model, as discussed later in this dissertation, to calibrate the probability logistic function in the simulation to account for the driver's behavior at signalized intersections.

2.3 EILS, SILS, and HILS Simulation Platforms

A previous effort examined the impact of using the EILS, SILS, and HILS approaches in the evaluation of traffic control (Stevanovic et al., 2009). The researchers concluded that the HILS and the SILS were able to provide more consistent and realistic signal timings compared to the EILS, especially in the case of coordinated-actuated controller operations. However, for intersections with pre-timed signal control and isolated actuated control, the three methods provided similar results. In general, the SILS and the

HILS were very similar when used in assessing the operational performance and results. This section presents a review of the literature on the EILS, SILS, and HILS platforms and the associated system components and standards required for the HILS implementation.

2.3.1 Emulator-in-the-loop Simulation

As previously mentioned, the EILS is the simplest approach among the EILS, SILS, and HILS approaches and the commonly used method for signal state generation both in practice and research (Arafat et al., 2020; Ardalan et. al., 2020; AlShayeb et. al., 2021). Arafat et al., (2021) demonstrated the use of EILS modeling to assess the safety and mobility benefits of the Signalized Left Turn Assist (SLTA), a CV-based application at signalized intersections. The benefits of SLTA were analyzed in their study using a calibrated microscopic traffic simulation package that utilizes EILS. Real-world gap acceptance distribution was used in the calibration of the simulation model to better assess the impact of SLTA considering the real-world driver's behaviors at permissive left-turn signals. Hadi et al., (2021) developed a method to evaluate the safety benefits of RLVW using microscopic simulation that utilizes the EILS approach. The study results confirm that it is critical to calibrate the probability to stop on amber in the utilized simulation model to reflect real-world driver behaviors when assessing RLVW impacts. The study results showed that without calibration, the model was not able to assess the benefits of RLVW in reducing RLR and right-angle conflicts. Based on a surrogate safety assessment, the calibrated simulation models result showed that the CV-based RLVW can enhance the safety at signalized intersections by approximately 50.7% at the 100% utilization rate of the application, considering rear-end, and right-angle conflicts.

2.3.2 Software-in-the-loop Simulation

As stated earlier, SILS represents the integration of traffic simulation with a commercial traffic signal controller’s software. The SILS platforms can support complex signal timing settings and advanced controller parameters available in real-world controllers that are not supported by EILS (He et al., 2020). For example, one of the commercially available SILS in the VISSIM simulation tool is the ASC/3 controller software developed by Econolite. The ASC/3 controller consists of a Data Manager, Traffic Control Kernel, Controller Front Panel Simulator, and Dynamic Link Library (DLL) interface. The controller software provided in this environment has a total of 200 logic commands that can be utilized in traffic signal operations in the simulation model (Econolite, 2021). The Data Manager is a graphical interface that is used to input the controller data (e.g., timing plans and detectors data) and store this data in database files. The Traffic Control Kernel is the virtual controller core software that includes all the internal data inputs processing and guarantees consistency in signal control operation between the simulated SILS running in simulation and a physical signal controller. The Controller Front Panel Simulator is a Graphical User Interface (GUI) designed to replicate the controller's physical display and keypad. The DLL interface enables the simulation model to receive the controller status information and pass the detector information to the simulated controllers (He et al., 2020).

Zlatkovic et al. (2011) examined the operational implementation of transit signal priority (TSP) strategies using SILS. The authors compared the results from the simulation to the existing conditions and reported that the SILS is a powerful platform to analyze different aspects of TSP.

He et al. (2012) utilized the VISSIM ASC/3 Econolite SILS platform to evaluate the benefits of platoon-based multimodal signal control. The authors reported that the SILS can simulate the actual controller logic for actuated coordinated signals and transit signal priority (TSP).

Day and Bullock (2014) investigated the impacts of fixed and floating force-off parameters in signal controller settings using a SILS platform. The authors reported that the SILS can produce controller logic that is close to real-world traffic signal operations.

2.3.3 Hardware-in-the-loop Simulation

The HILS in this dissertation is intended to implement a platform for assessing the RLVW and investigating a solution that mitigates the uncertainties associated with the actuated signal controllers in a laboratory environment. The system is designed to incorporate microscopic simulation software, along with a physical actuated traffic signal controller in the loop.

The utilization of hardware-in-the-loop for testing and evaluating traffic signal controllers has been widely used in transportation research (Bullock et al., 2004; Engelbrecht 2001; Li and Mirchandani 2016; So et al., 2013; Koonce et al., 1999). The review of literature on the HILS in this dissertation is divided into two main topics:

a) Literature review on signal controllers in a hardware-in-the-loop

b) Literature review on testing CV applications in a hardware-in-the-loop

2.3.3.1 Signal Controllers in a Hardware-in-the-Loop

HILS integrates traffic simulation software and a physical traffic signal controller. With the HILS, the simulation software generates virtual traffic and virtual detector data and sends the information to the signal controller, which generates signal states and sends them back to the simulation model. The HILS platforms set the signal controller to react to the virtual detector calls as if they were coming from real-world detectors. The communication between the traffic signal controller and the traffic simulation package can be done either using a middleware interface or a hardware interface. The middleware is an interface that acts as a bridge between the traffic signal controller and the simulation platform. This communication can be achieved using the National Transportation Communications for Intelligent Transportation System (ITS) Protocol (NTCIP) standards by developing programs that send and receive Simple Network Management Protocol (SNMP) requests (Ma et al., 2018). The hardware interface is referred to as Controller Interface Device (CID).

In practice, it has been found that the existing traditional CIDs have some limitations, particularly when simulating multiple signals. Wang et al. (2017) refer to a special type of CID called Virtual Controller Interface Device (VCID) that uses the Ethernet cable to connect the simulation network to the signal controller utilizing the National Transportation Communications for ITS Protocol (NTCIP). The main difference between the CID and the VCID is that the CID is a hardware device that provides the connection through USB and serial cables. Each signalized intersection modeled in the simulation requires a separate CID. However, the VCID is a middleware that uses a software package to serve as the bridge between the actual traffic signal controllers and simulation software. In short, VCID makes it possible for simulation software to communicate with the actual signal controller over Ethernet. The VCID has three components as shown in Figure 2-1. These components are the Controller Communication Module (CCM), VISSIM Communication Module (VCM), and Processing Module. The

CCM is used to provide communication between the VCID/CID with actual traffic controllers. The VCM is used to provide communication between VCID/CID and VISSIM.

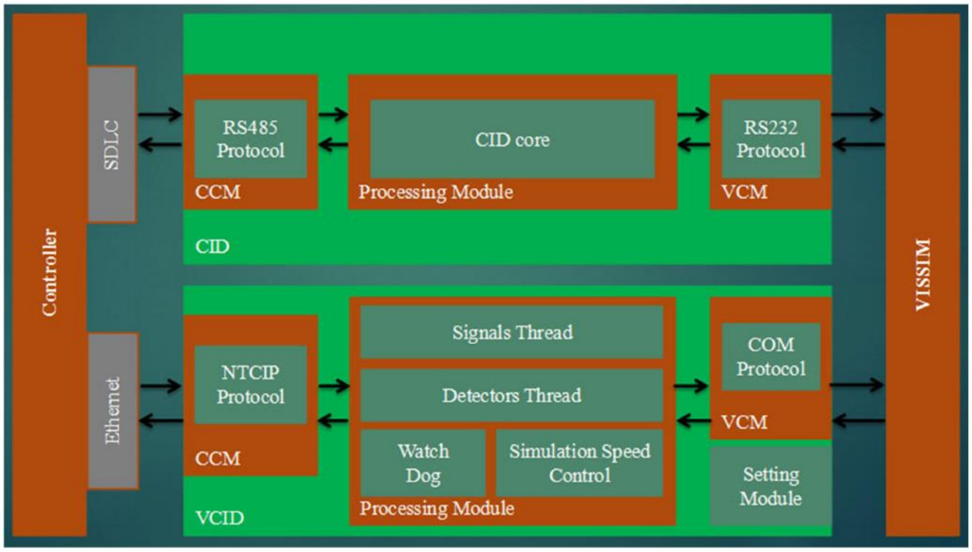

Figure 2-1: CID and VCID Architecture (Wang et al., 2017)

For CID, the CCM depends on RS485 protocol resolver and the VCM depends on RS232 protocol resolver. For VCID, the CCM is an NTCIP protocol resolver and the VCM depends on the Component Object Module (COM) in VISSIM. As shown in Figure 2-1, the platform uses a Recommended Standard 232 (RS-232) cable to connect the computer and the CID, while a Synchronous Data Link Control (SDLC) cable is used to connect the simulation tool to the traffic signal controller. Thus, the signal controller needs to be placed considering the SDLC cable length to be able to connect to VISSIM. However, the VCID uses an Ethernet cable which provides a more stable and convenient connection through the NTCIP communication protocol. Based on controlled experiments, the study results showed that the vehicle departure time, simulated travel time, and delay generated from using the CID-based platform are very similar to those generated based on the VCID-based platform.

The main advantage of utilizing a physical signal controller in the HILS is that it allows simulating realistic signal timing plans and advanced signal controller features in a risk-free laboratory environment.

A significant effort has been done in the academic literature in the past decades to test and evaluate signal controller algorithms using HILS. Stevanovic et al., (2009) examined the impact of using the built-in controller emulator (EILS) in the PTV's Verkehr In Städten SIMulationsmodell (VISSIM) simulation, software-in-the-loop simulation (SILS), and HILS approaches in the evaluation of traffic control. The researchers conducted the testing under scenarios with different signal operational strategies such as pre-timed, actuated, and actuated–coordinated. The study emphasized the importance of synchronizing the controller's clock with the simulation platform in real-time. Performance measures were obtained from VISSIM such as average delay, the average number of stops, average stopped delay, average speed, and total travel time. The researchers concluded that the HILS and the SILS were able to provide more consistent and realistic signal timings compared to the EILS, especially in the case of coordinated-actuated controller operations. However, for intersections with pre-timed signal control and isolated actuated control, the three methods provided similar results. In general, the SILS and the HILS were very similar when used in assessing the operational performance and results.

As described by Stevanovic et al., (2009), the HILS introduces different types of system hardware and software latencies that result from the simulation model, shared memory, CID, signal conversion, CID interface software, traffic controller, signal propagation, and signal transmission. The researchers reported four main reasons for latencies in the HILS as follows:

a) Propagation delay

b) Transmission delay

c) CID signal processing delay

d) Software processing

The propagation delay is defined as the data packet travel time required between one point and another via the CID USB cable to the traffic controller. The transmission delay is defined as the delay attributed to the size of the data packet. The CID signal processing delay is the time required by the CID to convert data from analog to digital or vice versa. In order to minimize the impacts of these latencies, the researchers recommended adjusting the controller's corresponding time of day plan and starting the traffic signal controller and the simulation model concurrently to achieve the best clock synchronization.

Sanchez et al. (2009) tested a ramp metering algorithm that prevents on-ramp queues from spilling over to upstream streets using HILS that includes a controller interface device (CID) that interfaces with a 2070 traffic controller. The researchers reported that this tool was able to successfully test the performance of the algorithm.

Klanac (2016) modeled six coordinated traffic signal controllers using a HILS environment integrated with the VISSIM simulation using CIDs for information exchange. Two testing scenarios were performed; the first scenario included twelve RBC-controlled intersections (which is the emulator of the controller in the VISSIM software), while the second scenario included a combination of six RBC-controlled intersections and 6 HILS intersections. The six physical controllers were Econolite (Cobalt), Siemens (m50), PEEK (ATC-1000), Trafficware (900 ATC), Intelight (2070-LDX), and McCain (ATC ex). The methodology was based on the HIL concept where the traffic signal controller receives virtual detector actuations from the simulation, and the simulation tool receives phase states from the controller. The study used CID to enable the connection between VISSIM and the signal controller along with a Trafficware TS2 Test Box software to enable the communication between the controller and the connection to the RS232 port to run the Trafficware CID. The study conducted a comparative analysis between the coordination of signalized intersections controlled by the RBC virtual controller and the coordination of signalized intersections controlled using a HILS controller configuration. The study results showed a significant difference between the results of the simulation based on the two modeling methods.

2.3.3.2 CV Applications in a Hardware-in-the-Loop Environment

Gelbal et al. (2020) evaluated a combination of the RLVW and the Green Light Optimized Speed Advisory (GLOSA) applications using a HILS testing platform. The researchers integrated a roadside unit and a traffic cabinet in a simulation environment to allow the testing of different scenarios. The study results successfully showed the ability of the developed HIL platform in generating both an optimal speed advisory for passing at the green light and providing red-light violation warnings. However, the researchers assumed fixed green intervals with no uncertainty in the end-of-green time.

Ma et al. (2018) developed a HILS proof-of-concept platform for use in testing the CV-based Cooperative Adaptive Cruise Control (CACC) application. The HILS system includes a physical connected automated vehicle (CAV), field test track, CV equipment, and a microscopic simulation tool. Figure 2-2 shows the developed framework and architecture of the HIL system.

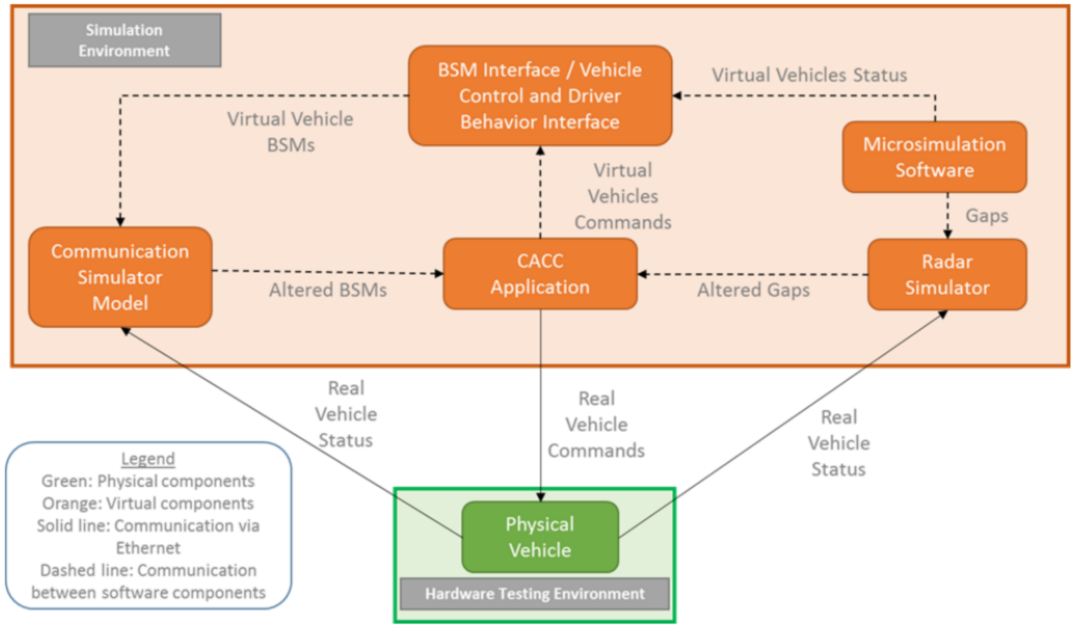

Figure 2-2: CACC HIL Architecture (Ma et al., 2018)

In Figure 2-2, the Ethernet communications are represented by the solid lines between the CAV and the PC. The data exchanges between the software components are represented by the dashed lines. Real-time virtual vehicle data are sent from the simulation software to the HIL interfaces, which then converted the information into basic safety messages (BSMs). The simulated BSMs and the radar measurement gaps generated from the simulation are then sent to the CACC application. This allows the CAV to understand the location of the virtual vehicles. The CACC combines the previous information and generates speed commands. The researchers reported that the developed algorithm is capable of testing more complex CV-based V2V applications. The study results showed a successful demonstration of the CACC application.

Another study by Ma et al., (2018) developed a HIL platform where they integrated a vehicle-in-the-loop for testing CV-based V2I application. The platform integrated a real CAV, a traffic signal controller, and a microscopic simulation tool (VISSIM). The researchers reported that the HILS improves the validity of CV-based testing results by incorporating the real-world vehicle's trajectories in a simulation environment. The platform was used to test and quantify the potential benefits of a CAV queue-aware signalized intersection approach and departure (Q-SIAD) application. The Q-SIAD algorithm combines the signal phase and timing (SPaT), downstream queue length, vehicle's acceleration/deceleration, and the status of other vehicles to generate recommended speed profiles. Figure 2-3 describes the developed framework and architecture of the HIL system.

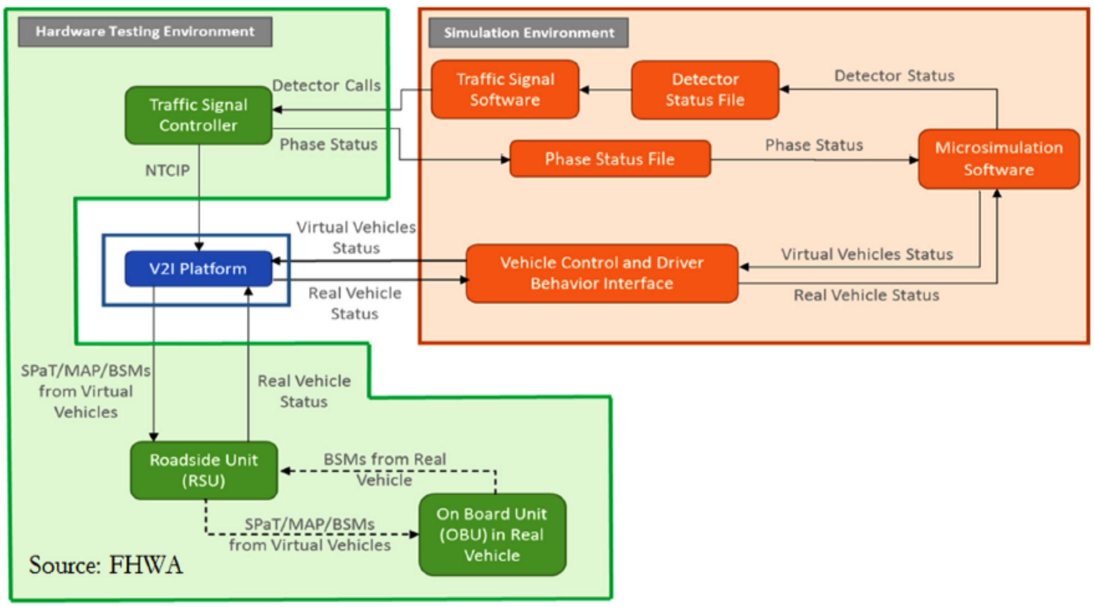

Figure 2-3: Q-SIAD Architecture (Ma et al., 2018)

As shown in Figure 2-3, VISSIM was used to generate the virtual background traffic and then sends the virtual detector actuations and the vehicles' status to a middleware called the V2X Hub. The V2X hub is an open-source software developed by the Federal Highway Administration (FHWA) that encodes and decodes CV messages between the vehicles and the infrastructure. The V2X Hub utilizes plugins to translate messages between different devices and connected vehicle applications on the RSE. The study results showed the ability of the developed algorithm in generating recommended speed profiles for testing CAVs.

Liu and Feng (2019) developed an augmented reality testing environment based on the vehicle-in-the-loop (VIL) concept that combines a microscopic simulation platform with a real-world CAV testing facility. The researchers utilized the developed reality environment for testing three scenarios that include red-light running, railway crossing, and traffic signal priority, which could be easily implemented in CV-based V2I applications. VISSIM was used in the study to generate virtual background traffic that interacts in real-time with the real-world CAVs and traffic signals, to provide a complete testing environment. This realistic platform allows the CAVs to interact with other vehicles in a safe and cost-effective environment to overcome the limitations of real-world CAV testing facilities where the CAVs only communicate with each other and with the infrastructure equipment. In addition, this testing environment allows testing multiple scenarios that require the interaction of other modes of travelers such as cyclists and pedestrians. Figure 2-4 shows the framework and architecture of the developed augmented reality test environment. The platform consists of real-world system components such as RSEs, vehicle detectors, traffic signal controllers, real CAVs, and roadside processors (RSP). The CAVs communicate the vehicle information with the RSUs through DSRC. The RSP is responsible for receiving the simulation data and sending that information to the infrastructure equipment, in addition, it sends the processed information from the infrastructure equipment to VISSIM.

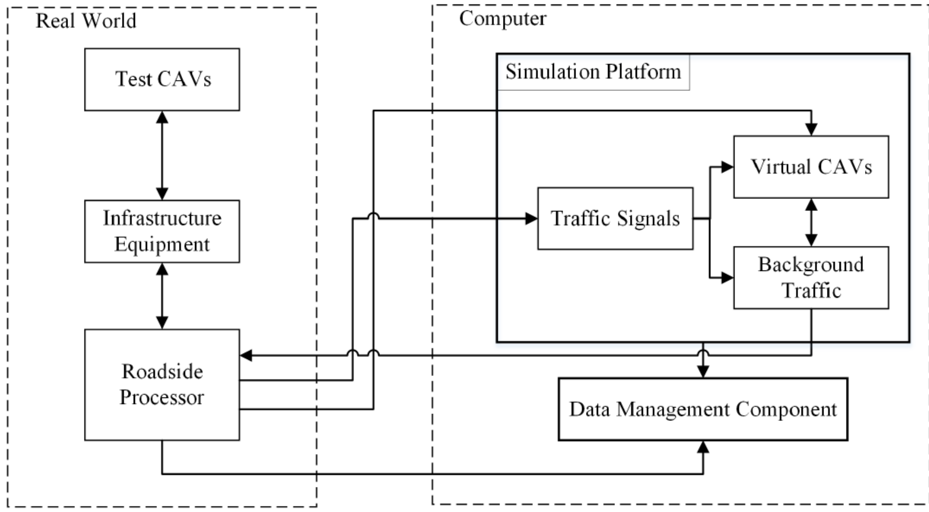

Figure 2-4: Augmented Reality Environment Architecture (Liu and Feng 2019)

The real-world traffic network was replicated in the simulation platform in terms of traffic signals and road geometries. Virtual traffic signals in the simulation model were synchronized with the real signal in the test facility. The virtual CAVs are generated and updated in the simulation based on the vehicle information sent from the real-world CAVs, which is synchronized with the Virtual CAVs in the simulation model. The behaviors of the virtual vehicles in the simulation are synchronized with real vehicles. The study results successfully showed the ability of the developed augmented reality environment in providing an accelerated evaluation approach and generate different testing scenarios for CAV applications.

Szendrei et al. (2018) developed a HILS platform for testing CV applications. The platform consists of an open-simulation software, which is the Simulation of Urban Mobility (SUMO) software; an orchestrator, which manages all elements of the HILS system components; and commercial CV devices. Figure 2-5 shows the detailed architecture of the developed HIL. As described by the researchers, a specific what is referred to as “gpsfake” is available for each RSE and OBE in the system. A gpsfake is a test harness modified with relevant extensions belonging to the GPS (Global Positioning System) that continuously produces the location data required by the V2X protocol stack of the RSE and OBE units. As shown in Figure 2-5, the communication between the supplemental modules and the Orchestrator is based on TCP (Transmission Control Protocol) sockets. A socket is a combination of an IP address and a port number of a two-way communication link. The researchers integrated SUMO in the HIL platform by using TraCI (Traffic Control Interface) which provides the appropriate control and simulation visualization.

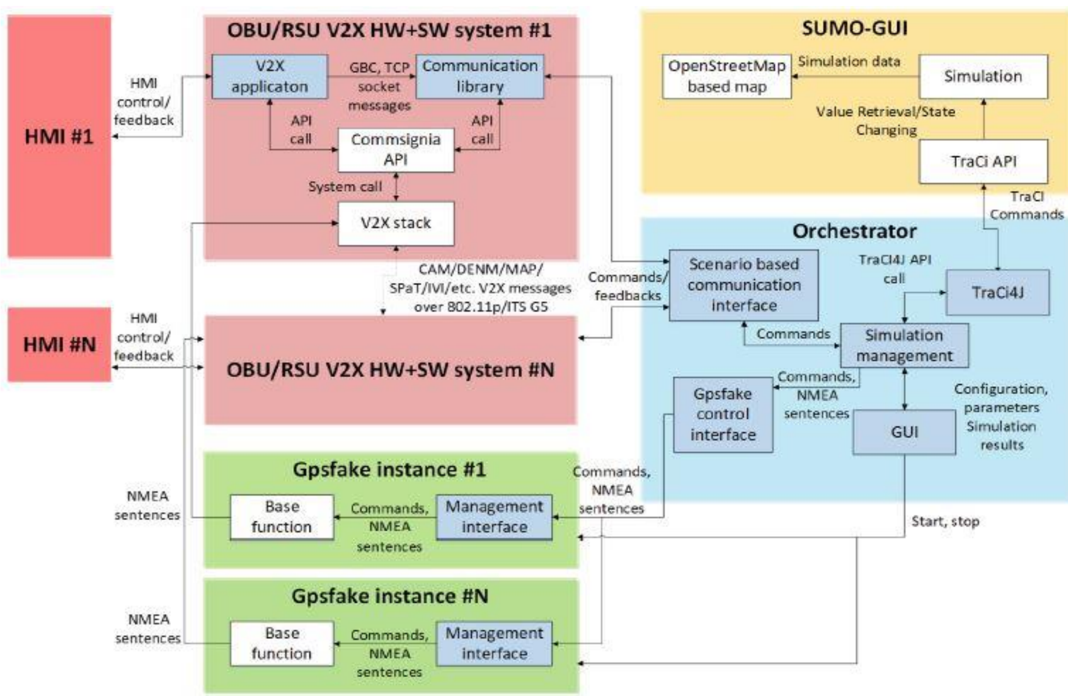

Figure 2-5: HIL V2X Simulation Architecture (Szendrei et al., 2018)

The researchers reported that the proposed HILS framework offered a cost-efficient tool for testing and evaluating CV-based applications in a laboratory environment.

Yun et al. (2012) utilized a HILS testing platform for comparing various emergency vehicle preemption (EVP) strategies using a coordinated-actuated traffic signal controller. The testing platform consisted of VISSIM connected to four Type 170 signal controllers to examine the performance of different EVP strategies such as the short-way and the dwell strategies. The researchers implemented the platform to model four coordinated-actuated signalized intersections. The study results showed that the short-way strategy had the best performance in minimizing the impacts of EVP.

Sunkari et al. (2018) developed a HILS platform that enables controlled field testing of CV-based applications in an augmented testing environment. The HILS utilized a microscopic simulation tool to generate detector calls that are sent to the traffic signal controller to operate in an actuated mode and receive SPaT from the controller. The researchers also implemented this testing environment in a real field test to generate realistic scenarios. The HILS consisted of hardware components such as an Econolite ASC-3-2100 SPaT-enabled traffic signal controller and CV components such as an Arada Commando RSU and Arada Mini 2 OBU. The HILS integrated software modules including a microscopic traffic simulation tool (VISSIM). The developed HILS provides a platform for testing the CV SAE J2735 messages including the SPaT, MAP, and BSM messages. The results of the study showed that the developed HILS platform is capable of testing various CV-based applications in a cost-effective and risk-free manner.

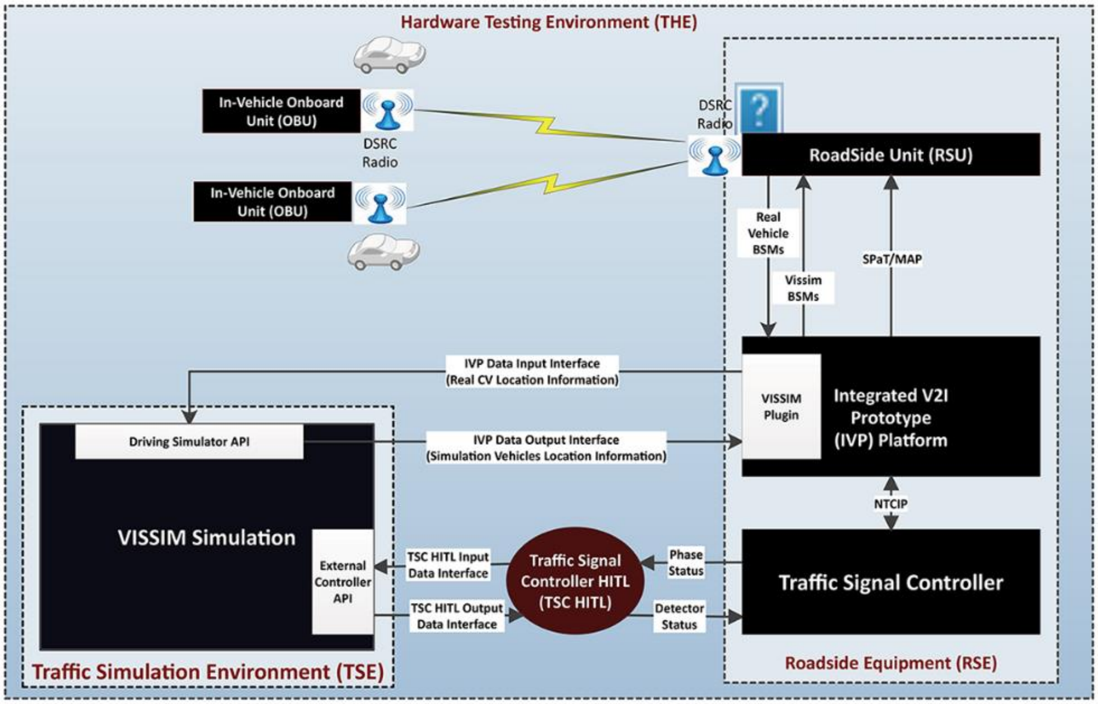

Figure 2-6: HILS Architecture (Sunkari et al., 2018)

Similar to the previously reported HILS architectures in the literature, this HILS developed by Sunkari et al. utilized VISSIM for sending detector calls to the traffic signal controller to operate in an actuated mode and receive SPaT messages from the controller at the test intersections. Using flat-earth approximation, the traffic simulation environment converted the local x-y coordinates of VISSIM to real-world latitude and longitude coordinates using a reference point whose x-y coordinates are known in VISSIM and on the world map. The HILS environment enabled simulated CV data to communicate with the RSE and OBE and to receive BSM from real vehicles. The developed HILS platform included an integrated V2X Hub that broadcasts and receives SAE J2735 messages through DSRC communication. The researchers developed a new VISSIM plugin in the V2X Hub that generates BSM messages for the virtual vehicles in the simulation and send them to the real CVs in the test intersection through the installed RSUs. In addition, the VISSIM plugin sends the latitude and longitude of the real CV to VISSIM and converts the latitudes and longitudes to x-y coordinates of VISSIM. The V2X Hub also included SPaT plugins for receiving the SPaT data from the signal controller and broadcasting the SPaT messages to the CVs via the RSU. Moreover, the MAP plugins in the V2X Hub were used to generate the MAP messages. The results of the study showed that the developed HILS platform is capable of testing various CV-based applications in a cost-effective and risk-free manner.

Chowdhury et al. (2018) evaluated the performance of different methods for modeling traffic signal operations in microscopic simulation in a basic actuated mode for an isolated signalized intersection in VISSIM. The authors used several sets of traffic and signal performance measures in the evaluation. The study concluded that there were significant differences in the results between the examined signal controller modeling platforms. The results showed that these differences are large enough to have a significant impact on the final model outcomes. The authors reported that these differences are caused by communication delays and the differences that exist in the internal controller logic. In addition, the authors reported that the inconsistent initialization of each signal controller in the simulation environment introduces some differences in the results.

2.4 Summary

Microscopic traffic simulation has been widely used in the academic literature for the evaluation of transportation systems in a risk-free environment (Appiah et al., 2013; Kaisar et al., 2019; Bullock et. al., 2004; Alzoubaidi et al., 2021; Chowdhury et al., 2018; Iqbal et. al., 2021; Ardalan et. al., 2020; AlShayeb et. al., 2021). In addition, most of the research studies that evaluate the Adaptive traffic control systems (ATCS) and traffic signal operations utilize VISSIM as a microscopic simulation tool (Dobrota et al., 2020).

This chapter presented a comprehensive literature review on using microscopic simulation and simulators in modeling CV-based RLVW applications and a review of studies that utilized EILS, SILS, and HILS to model CV applications.

2.4.1 Summary of RLVW Improvements

As described by Stephens et al., (2015), RLVW reduces the number of incidents between red-light running violators and cross-traffic. The application aids drivers by informing them if their vehicles are on trajectories to violate a red light at a signalized intersection, thereby potentially causing a collision with cross-traffic vehicles. RLVW increases drivers' awareness of approaching signalized intersections since it provides a timely on-board message to the driver to begin braking, based on vehicle operating conditions and roadway conditions. In addition, the application provides real-time calculation of safe deceleration and speed based on current conditions. The RLVW application includes the capability of capturing detailed maps of intersection geometries in real-time via roadside equipment. The lane-level vehicle positioning capabilities allow for lane-specific system awareness to help determine the intended travel through the intersection (i.e., straight, turn left, or turn right). The application can also incorporate current road and weather condition data from the infrastructure along with available vehicle telematics data to calculate the minimum distance necessary to stop under current conditions. The application provides an alert and, if needed, a warning within sufficient time for the driver to react and respond appropriately.

2.4.2 Summary of Studies on Modeling CV-based RLVW Applications

Researchers relied on field observations or driving simulators when assessing the effects of RLVW. Regarding simulators, the results showed that participants react more quickly to the change in traffic lights in the presence of RLVW. Some researchers reported that the RLVW reduces the drivers' likelihood to make go decisions at the onset of yellow 86 times compared to unequipped vehicles. Some studies pointed out that the utilized warning system was more effective in sending violation warnings when activated at a distance of 50 feet or 100 feet upstream of the stop line. Regarding the field testing of the RLVW, the results showed a reduction in red-light violations and consequently intersection collisions. Some researchers used microscopic simulation to model the RLVW application. However, the majority of the reviewed studies utilized the typical parameters used in calibrating microscopic simulation models and did not calibrate the microscopic driver behaviors in the model considering the probability of stopping-on-amber that impacts the red-light running.

CHAPTER 3
METHODOLOGY

This chapter describes the methodology used to support the goal and objectives of this research. The first section, the methodological framework, provides an overview of the methods of this research. In addition, it describes the detailed methods used to build the simulation environments required for testing the CV-based RLVW algorithm in the EILS, SILS, and HILS. A detailed description of each step is then presented in the subsequent sections.

3.1 Case Study Development

A basic four-leg signalized intersection is modeled as shown in Figure 3-1. This study sets the parameters of the signal timing including the minimum green times, maximum green times, yellow intervals, all-red intervals, and passage times according to the Traffic Signal Timing Manual published by the Transportation Research Board (Urbanik et al., 2015). The major street signals are set to continuously Rest-in-Green.

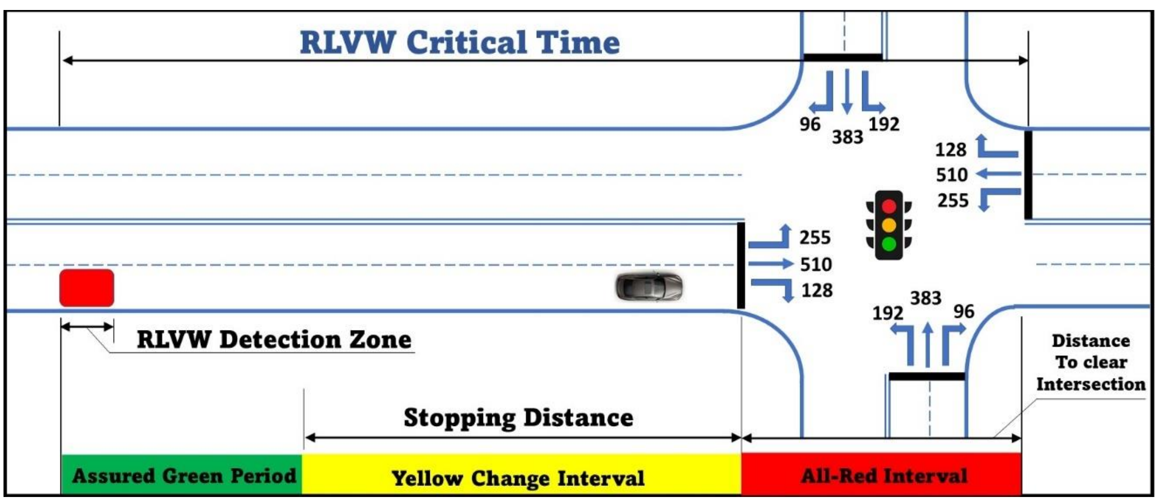

Figure 3-1: Case Study Signalized Intersection for Modeling RLVW Application

The signalized intersection shown in Figure 3-1 is modeled with the exact same conditions and signal controller parameters in the three tested simulation platforms (i.e., EILS, SILS, and HILS). The signal controller parameters in the three platforms were identical including the phase regime (which is the NEMA 8-phase regime), phase sequence, phase minimum recall, dual entries, and signal timing plans. In addition, the geometry and traffic-related parameters in the utilized models were set at the same values including those for traffic volumes, desired speed distributions, headways, driving behavior, geometry, etc. First, a cross-evaluation of the performance of the RLVW using EILS, SILS, and HILS platforms is conducted under pre-timed signal operation and semi-actuated signal operation with moderate traffic demands. Then, the HILS is selected to investigate a proposed solution to mitigate the uncertainties of the end-of-green associated with the semi-actuated signal operation with moderate traffic demands. Two additional scenarios with increased traffic demand (10% and 20%) using the HILS platform are analyzed to investigate the impact of the demands on the results of the analysis.

This study uses the PTV's Verkehr In Städten SIMulationsmodell (VISSIM) Version 20 as the microscopic simulation tool to model a test network and to assess the impacts of the signal control operation on the performance of the CV-based RLVW application in the simulation environments (PTV Group, 2020). The demands for the left-turn and through movements on both the northbound and southbound approaches are set to be 192 vehicles per hour and 383 vehicles per hour, respectively. The demands for the left-turn and through movements on both the westbound and eastbound approaches are set to be 255 vehicles per hour and 510 vehicles per hour respectively. These demands represent the moderate traffic demands scenario (i.e., base case scenario) based on the degree of saturation at the signalized intersection. The degree of saturation is calculated according to the Traffic Signal Timing Manual (Urbanik et al., 2015) as shown in Equation 3-1.

$$\text{Degree of saturation (x)} = \frac{v\,C}{s\,g} \tag{3-1}$$

where,

v = demand volume of the subject movement,

C= cycle length (sec),

S= saturation flow rate (veh/hr),

g= effective green (sec),

Each of the eight movements has one exclusive lane. The RLVW was applied to the through movements for evaluation purposes under pre-timed signal control and semi-actuated signal control.

Various sets of signal timing measures of effectiveness (MOEs) and RLVW performance measures are extracted from the output files produced by the simulation tool. The signal timing measures utilized in the comparison include the average green times and the total number of occurrences of each actuated phase. In addition, the RLVW assessment is done based on mobility and safety performance measures. The mobility measures are the stopped delay, the number of stops, approach delay, queue length, and the number of queue-stops based on simulation model outputs. The average stop delay is defined in the utilized simulation tool as the aggregate sum of the stopped time of all vehicles for a particular time interval divided by the total entering volume for that movement. The number of stops is the average number of stops per vehicle due to signal control. The approach delay is the average delay of all vehicles obtained by subtracting the theoretical (ideal) travel time from the actual travel time (PTV Group, 2020).

According to the VISSIM user manual (PTV Group, 2020), the queue length is the maximum distance between a modeled traffic counter and the vehicle that meets the queue threshold. The queue threshold is based on the speed of the vehicle upstream of the traffic counter and ranges between 3.1 mph (i.e., queue start) and 6.2 mph (i.e., queue end). This study calculates the average arithmetic queue length for each time interval (1-hour simulation) by measuring the queue length at each time step upstream by the queue counter and the arithmetic mean is thus calculated per time interval. The number of queue-stops is the summation of the events where one vehicle that is just upstream of the back of the queue or within the queue falls below the defined speed to indicate queuing.

The safety measures involve collecting the total number of RLR events and surrogate measures related to the right-angle and the rear-end conflicts at the intersection approaches, which are the types of conflicts associated with RLR.

3.2 EILS and SILS Platforms Setup

As stated earlier, the utilized simulation tool has a built-in RBC logic that is capable of replicating the NEMA standards for actuated traffic signal controllers (PTV Group, 2020). For each simulation time step, the traffic simulator sends the virtual detector calls to the internal emulator which returns the signal state for the next time step. In this study, the RBC editor Graphical User Interface (GUI) is used to input the signal timing plans according to a NEMA eight-phase setting and to set up the assignment for detectors for each signal group.

The SILS platform used in this study consists of a traffic simulator tool, an Econolite ASC/3 virtual controller supported by the utilized simulation tool, and a graphical user interface that allows for exchanging information. In each time step, the traffic simulation model constantly updates the location of the vehicles in the network and the status of the detectors (i.e., ON/OFF), according to the vehicle actuation/presence. Accordingly, the vehicle detector calls are transferred to the ASC/3 virtual controller logic, which sends back the signal state to the modeled signal heads based on the predefined actuated signal timing parameters.

3.3 HILS Platform Setup

An important contribution of this dissertation is the development of a full laboratory HILS environment for testing CV-based V2I applications. This environment integrates different types of CV system hardware and software components that will be beneficial not only for conducting the current research but also for future related research.

3.3.1 Development of a Full HILS Laboratory Environment

This section presents the developed HILS environment and the necessary components for building the system including both hardware and software. The main goal of the integrated HILS is to conduct full V2I experiments in a laboratory environment and test the CV messages used by various CV-based applications.

Figure 3-2 shows the framework and hardware components of the developed HILS test environment.

Figure 3-2: Hardware Components for the Developed HILS Environment

The physical traffic signal controller used in this study is Econolite Cobalt G-series with the EOS 140-1048-2CV firmware. Cobalt includes a Linux-based Engine Board that is compliant with the ATC standard for a NEMA standard TS2 Type-2 input/output (I/O) connectors: four Ethernet ports, two USB ports, and a Secure Digital (SD) Card slot. Table 3-1 shows the hardware details for the signal controller. This controller is designed by Econolite to provide a combination of Actuated Traffic Controller (ATC) open architecture functionality with advanced technology and applications. Cobalt also features a hardened seven-inch touchscreen user interface matched with a Linux-based operating system, to allow the ease of programming and access to functions.

Table 3-1: Econolite Cobalt Hardware Details

Item no.	Item	Description
1	ATC Engine Board	Fully compliant with the ATC Standard
		233MHz Power QUICC II Pro-processor
		128Mbytes of DDR2 DRAM memory
		64 Mbytes of FLASH for storage
		2MB of SRAM memory
2	Two integral Ethernet switches	Enables Cobalt's enhanced graphical user interface
		Touch screen capability
3	Two USB 2.0 ports	Update application software
		Upload or download configuration
		Upload logged data
4	Data key socket	Optional 3.3V Data key
5	Three communications ports	NEMA-ATC SDLC serial port 1
		25 pin serial port 2
		9 pin console serial port
6	Operating system	Linux 2.6.3x or later kernel and Board Support Package (BSP)
		Compliant to ATC Standard

As shown in Figure 3-2, the HILS laboratory environment is built at Lehman Center for Transportation Research (LCTR) at Florida International University (FIU). Tables 3-2 to 3-4 below show the system components.

Table 3-2: HILS Hardware Components

Item no.	Item	Model
1	Econolite Traffic Signal Controller	Cobalt G-series with EOS 140-1048-2CV
2	Trafficware Traffic Signal Controller	Commander TS2-2 DSRC Enabled
3	SIEMENS Roadside Unit	ESCoS RSU 1.2 WebGUI
4	Controller Interface Device (CID)	Trafficware
5	Desktop computer (Linux Operating System)	DELL

Table 3-3: HILS Software Components

Item no.	Item	Developer – Model – Vendor
1	Middleware	BAA_HITL FIU_HILS
2	Microscopic Traffic Simulation Package	VISSIM V.20
3	V2X-Hub	BATTELLE
4	TS2 TestBox	Trafficware
5	IP packet sniffer	WireShark

Table 3-4: HILS Cables

Item no.	Item
1	Cheater Chords – power connectors A
2	Ethernet Cables
3	RS232 Cables
4	SDLC Cables
5	Power Cables
6	HDMI Cables - Converter

3.4 Signal Controller Operations in the Simulation Platforms

The study compared the performance of the modeled CV-based RLVW application under pre-timed signal control and semi-actuated signal control. The main goal of this comparison is to identify the impact of the traffic signal operations on the performance of the RLVW.

3.4.1 Pre-timed Signal Controller Setup

As previously mentioned, the pre-timed signal controller parameters in the simulation platform are based on the NEMA 8-phase regime. Pre-timed control consists of a series of intervals that are fixed in duration. Collectively, the preset green, yellow, and red intervals result in a deterministic sequence and fixed cycle length for the intersection.

3.4.2 Semi-actuated Signal Controller Support of RLVW

As mentioned in the review of literature, a potential design element for an actuated signal controller support of the RLVW is to dedicate an AGP to mitigate the uncertainty of the remaining green time due to the actuated signal operation. According to the discussion in the USDOT effort (ITE CI committee, 2021), the following terms, definitions, acronyms, and abbreviations are used in this section as shown in Table 3-5.

Table 3-5: Definitions and Acronyms (ITE CI Committee, 2021)

Item no.	Term	Definition
1	Connected Intersections (CI)	An infrastructure system that broadcasts the signal, phase and timing (SPaT), mapping information and position correction data to On-Board Units and Mobile Units.
2	Approach Speed	The assumed speed for through movement used by the CI infrastructure for the RLVW application. This speed is the 85th percentile speed
3	Assured Green End Time (AGET)	When it can be determined with a high level of certainty by the CI/TSC infrastructure, AGET is the time indicating the end of a green signal indication for a through movement. It means that the end of the green indication will occur except for failure, preemption, or something else outside of the CI/TSC infrastructure's control. When applied, the AGET is always equal to or greater than the current minimum green end time of the movement.
4	RLVW Critical Time	The time required to traverse the length of the RLVW Detection Zone, the stopping distance to the stop line, and the distance to clear the intersection.
5	RLVW Detection Zone (RDZ)	The area on a through movement lane that is used to detect vehicles for the RLVW operation. The RDZ is upstream from and adjacent to the stopping distance to the stop line.

The parameters needed to estimate the AGP are the approach speed, the stopping distance, and the time required to clear the intersection, as shown in Figure 3-1. First, the impact of the AGP on the performance of the RLVW application is investigated under moderate traffic demands. Then, two additional scenarios with increased traffic demand (10% and 20%) are analyzed to investigate if the AGP can generate the same trends using the HILS platform. The utilized approach speed in the calculation of the AGP is the 85th percentile speed, as discussed in the Connected Intersection effort funded by the USDOT mentioned earlier (ITE CI committee, 2021). This speed is recognized as a reasonable speed to use in calculating the AGP since most drivers on the road consider it to be safe and reasonable under ideal conditions.

According to the discussion and the deliverable from the USDOT effort (ITE CI committee, 2021), the RLVW detection zone is an area on a through movement lane where the vehicle is to be detected through vehicle-to-infrastructure communication to support the RLVW application. The detection zone location is set such that the distance from the stop line to the RLVW detection zone is equal to a full stopping distance plus the AGP. If the CI detects a vehicle in the RLVW detection zone, the associated movement is in green, and the signal controller is not terminating the movement, then the controller needs to set the minimum end time of the movement phase to the current time plus the AGP. If the CI determines that a movement currently in green is to terminate, the controller provides an assured green end time (AGET) that is equal to or greater than the minimum end time of the phase. The controller provision of the AGET allows the RLVW application on the OBE to receive accurate SPaT messages. Vehicles upstream of the detection zone will have enough time to stop before the stop line.

Figure 3-1 shows the parameters needed to estimate the AGP, the yellow interval is designed to allow one safe stopping distance away from the stop line and can be calculated from Equation 3-2.

$$y_t = t_{PR} + \frac{1.47\, V_{approach}}{2 \times (a + 32.2G_i)} \tag{3-2}$$

where,

y_t = length of the yellow change interval (sec.),

t_{PR}= perception reaction time (sec.),

$V_{approach}$= approach speed (85th percentile speed, mph),

a = deceleration rate of vehicles (ft/s^2), and

Gi = approach grade.

The time required for the vehicle to cross the intersection and clear its back bumper past the far curb line (or crosswalk line) before conflicting vehicles are given the green can be calculated from Equations 3-3. This is used as an all-red interval.

$$ar_i = \frac{w + L}{1.4\, S_{15i}} \tag{3-3}$$

where,

ar_i = time of the all-red phase (sec.),

w = width of the street being crossed from curb to curb (ft),

L = length of a standard vehicle usually taken to be 18 feet,

S_{15i} = 15th percentile speed of the approaching traffic (mph).

The RLVW critical time required for the calculation of the AGP is the summation of the AGP, time to traverse the stopping distance (i.e., yellow change interval), and time to clear the intersection; as shown in Equation 3-4. Finally, the AGP can be calculated by subtracting the yellow interval and all-red interval from the RLVW critical time.

$$t_{RLVW} = AGP + y_t + ar_i \quad (3\text{-}4)$$

where,

t_{RLVW} = red-light violation warning critical time,

AGP = assured green period.

3.5 RLVW in the HILS Environment

This section describes the methods used to build the simulation environment required for testing the CV-based RLVW algorithm in a HILS. As previously mentioned, the physical traffic signal controller used in this study is Econolite Cobalt G-series with the EOS 140-1048-2CV firmware. The actuated controller model is based on the National Electrical Manufacturers Association (NEMA) standards for signal controllers (NEMA, 2016).

The communication between the traffic signal controller and the traffic simulation package can be done, either using a middleware interface or a hardware interface such as CID. In this study, middleware is used to eliminate some of the system hardware latencies reported in the literature as a result of using the CIDs (Stevanovic et al., 2009). The CID introduces different types of delays associated with signal conversion, CID interface software, signal propagation, and signal transmission. The propagation delay is defined as the data packet travel time required between one point and another via the CID USB cable to the traffic controller. The transmission delay is defined as the delay attributed to the size of the data packet. The CID signal processing delay is the time required by the CID to convert data from analog to digital or vice versa (Stevanovic et al., 2009). The utilized middleware in this study eliminates the propagation delay of CIDs because of using the computer Random Access Memory (RAM) in transferring the data. Cunningham (2018) reported that transferring internal data over the RAM is 10 times faster than using USB ports. For example, modern DDR4 RAM provides peak data transfer rate of around 25,600 MB/s while USB ports give a maximum data transfer rate of 2.5 GB/s (2,500 MB/s) (Cunningham, 2018). Figure 3-3 shows the system framework and data flow between different components of the utilized HILS platform.

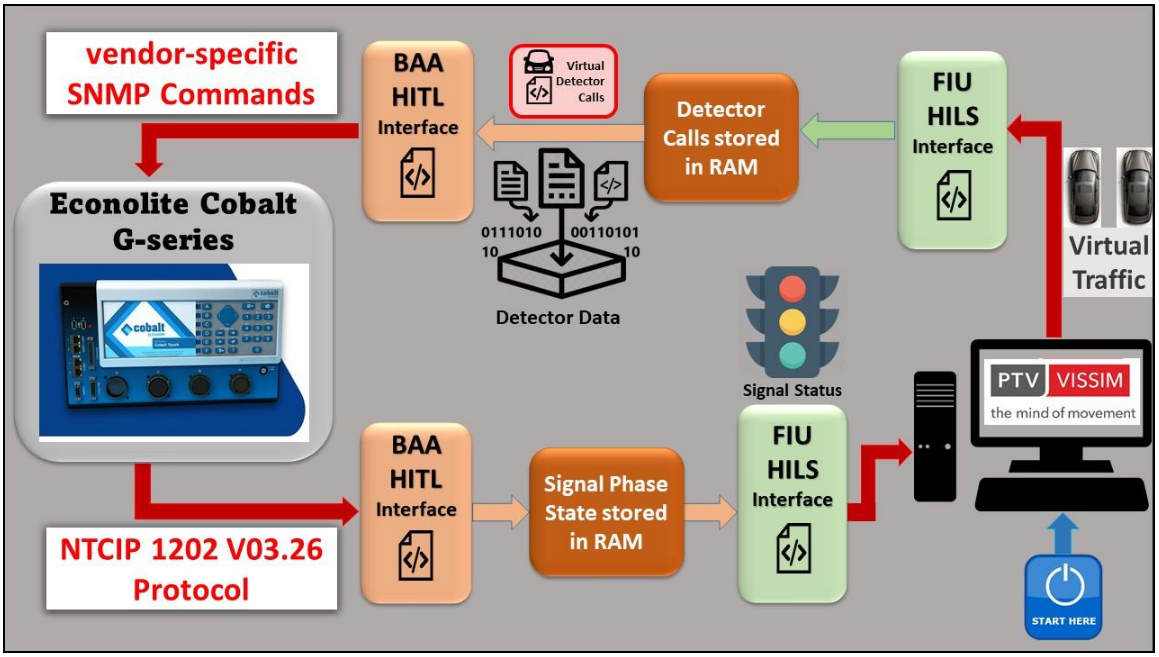

Figure 3-3: Data Flow between the HILS Hardware and Software Components

The developed middleware in this dissertation is based on the NTCIP communication standards and consists of two main programs. The first program is called BAA_HITL and was developed in a previous Federal Highway Administration (FHWA) project (Ma et al., 2018). The second program is developed as part of this dissertation work, which is called FIU_HILS. This study integrated both programs in one compiled solution module using the C# programming language, as shown in Figure 3-3. The traffic signal controller is connected over the network with a fixed MAC address and IP address that are used to communicate with the BAA_HITL and FIU_HILS programs to receive detector calls from the simulation and to send signal phase states to the simulation.

VISSIM Version 20 is used in this system to generate virtual background traffic (PTV Group, 2020). An external signal controller module is developed using the signal controller Application Program Interface (SC-API) in the simulation tool. The simulation tool sends all detector data and virtual vehicle status data to the FIU_HILS interface, which then passes these data to the computer RAM. The BAA_HITL interface reads the detector calls from the RAM and sends these calls through SNMP commands (Case et al., 1989) to the Econolite Cobalt G-series controller. Figure 3-4 shows the vehicle detector placement in the simulation model along with the full middleware interface and the log window of the system. Each detector is assigned a port number corresponding to a specific signal phase number that is called over the detector channel. The assignment gives odd numbers to the left-turn movements and even numbers to the through movements.

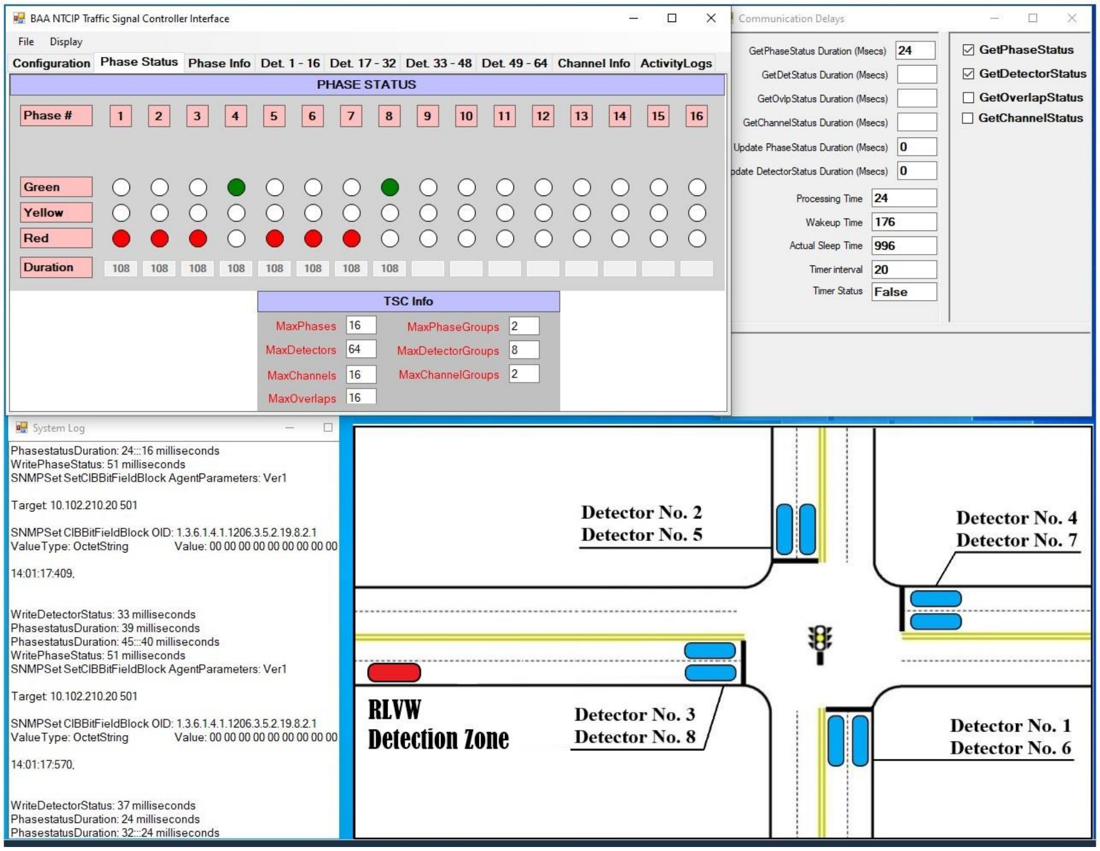

Figure 3-4 HILS Middleware Interface and Detector Setup

It should be noted that at the time of writing this dissertation the Cobalt controller does not support the extended vehicle detector object identifiers (OIDs) in the NTCIP 1202 version V03.26 standards. In order to overcome this challenge, this study implemented a set of vendor-specific SNMP commands provided by Econolite to support the vehicle detector actuations. Two SNMP objects are used to inject the vehicle detector inputs into the Cobalt controller. The first SNMP object establishes a Controller Input Buffer (CIB) bitmask and specifies the activation duration for each detector call in Deci-seconds. For example, a SET of an integer value equal to 50 on this object will retain the detector call for 5 seconds. The second SNMP object provides a bitmask (i.e., detector status) of ON and OFF values for bit values of 1 and 0, respectively.

Accordingly, the physical controller generates the corresponding phase status based on the received detector calls and sends the phase status back to the RAM of the PC running the middleware through the BAA_HITL interface. Then, the FIU_HILS interface uses the Component Object Model (COM) to enable the virtual signal heads in the simulation tool to be synchronized with the phase status of the physical traffic signal controllers in real-time.

The Windows Command Prompt (CMD) is used as the command-line interpreter for placing the SNMP commands to check the connectivity and communication between the simulation model and the physical signal controller. The SNMPWALK application is installed and used to place the SET and GET requests to/from the traffic signal controller. SNMPWALK is a simple network management protocol application that uses SNMP GETNEXT requests to query a network device with an IP address for information (Case et al., 1989). An object identifier (OID) may be given on the command line. This OID specifies which portion of the object identifier space will be searched using GETNEXT requests. All variables in the subtree below the given OID are queried and their values are presented to the user.

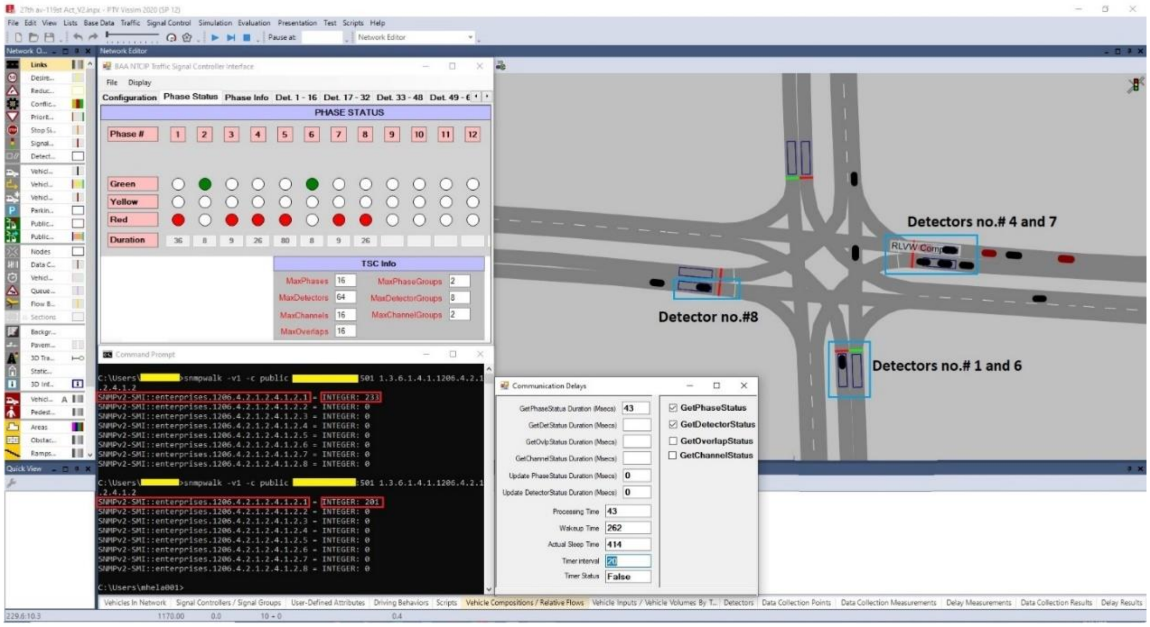

Figure 3-5 HILS middleware and SNMPWALK queries

For example, as shown in Figure 3-5, the CMD window sends two GET requests and received the integer values of (integer = 233 and integer = 201). The corresponding binary values for the SNMP requests are (11101001 and 11001001), respectively. These binary values, arranged from right to left, define the status of each detector where “0” means OFF and “1” means ON. During the first SNMP request, it can be confirmed from the simulation that vehicle detectors No. 1, 4, 6, 7, 8 are ON and vehicle detectors No. 2, 3, 5, are OFF (i.e., 11101001). After that, the vehicles heading downstream SB approach left the detector No. 6, so accordingly the second SNMP request returned a value of integer 201 (i.e., 11001001).

The actuated signal controller is programmed to rest-in-green on the major approach. This setup will force the green interval to serve the minor road only in the presence of a conflicting call. The major street has a pre-defined green phase time. When this time is reached, the intersection transits to green “Rest Mode” where the major street continues in green operation until either a pedestrian actuation, a cross-street vehicle actuation, or an eventual timing out occurs (ITE CI committee, 2021).

It should be noted that at the time of writing this dissertation, the EOS firmware 140-1048-2CV does not support the AGP. Thus, it was necessary to mimic the AGP in the simulation model in two main steps. First, a "dummy" detector is placed at the location of the RLVW detection zone as shown in Figure 3-4. The location of the RLVW detection zone is computed based on the 85th percentile speed of the subject approach. The dummy detector is responsible for detecting the approaching connected vehicles in the simulation and sending the information to the RSE to calculate the assured green extensions to the signal controller. This detector only detects the modeled CV vehicle class in the simulation model since conventional vehicles do not have access to the RLVW information and there is no need to provide the assured green period for these vehicles. When detecting a vehicle in the RLVW Detection Zone, the model uses the "Vehicle Detector Extend Parameter" according to the NTCIP 1202 V03.26 standards to model the AGP. This parameter is the period a vehicle detector actuation is extended from the point of termination when the phase is Green.

3.6 Simulation Network Calibration and CV-based RLVW Modeling

Drivers' behavior at the dilemma zone is an essential parameter in the modeling of RLVW and significantly affects the probability of violating a red-light. This behavior is mainly a function of the drivers' stop-go probability decisions during the amber interval. The accurate calibration of the probability distributions of this behavior in the utilized microscopic simulation model has a great impact on the validity of the RLVW simulation results.

3.6.1 Simulation Network Calibration

This section describes the methods used to calibrate the simulation model parameters to produce a realistic stopping probability on amber. The main objective is to demonstrate a method of network calibration to support the simulation modeling of RLVW. This method utilizes the real-world probability of stopping for the drivers approaching a signalized intersection during the amber interval. The calibration is conducted based on the vehicle trajectories obtained from the simulation model along with the use of logistic regression to replicate real-world drivers' behavior. It should be noted that the term "calibration" in this method is defined as the process of adjusting the base simulation model parameters to better replicate the results expected based on previous models derived from the literature using real-world drivers' behavior (Arafat et al., 2021a and Arafat et al., 2021b).

The calibration method is based on models borrowed from the literature to replicate the real-world drivers' behavior in the dilemma zones. The parameters of the utilized model are best fine-tuned based on local data if such data is available. Such data will become more widely available with the adoption of CVs and high-resolution controller data. Meanwhile, parameter values derived based on previous studies can be used, at least as starting points in the model calibration. Van der Horst and Wilmink (1986) collected field data from four signalized intersections in the Netherlands and proposed a log-linear stopping probability model that best fits the collected data. Sheffi and Mahmassani (1981) collected data from nine intersections in Kentucky and proposed a probit-stopping model that showed a much closer fit to the local driver behavior. Gates et al. (2007) updated the models proposed by Van der Horst and Wilmink (1986); and Sheffi and Mahmassani

(1981) based on data collected from six signalized intersections in the Madison, Wisconsin area to evaluate the drivers' stopping characteristics including deceleration rates, brake-response time, and red-light running violations. The Gates et al. (2007) study proposed an updated model to predict the drivers' stopping probability as shown in Figure 3-6. The dissertation utilizes this real-world stopping probability distribution to calibrate the simulation model to ensure that it better simulates the driving behaviors.

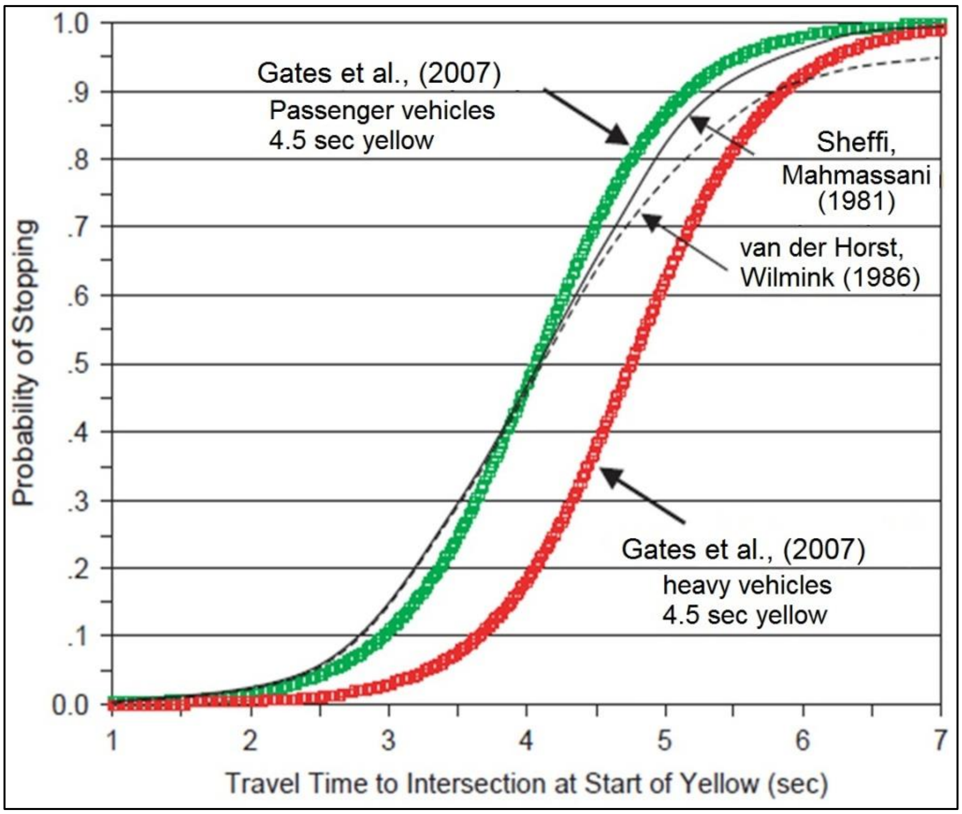

Figure 3-6: Drivers' probability of Stopping (Source: Gates et al., 2007)

PTV's Verkehr In Städten SIMulationsmodell (VISSIM) offers two methods of modeling the drivers' decision-making behavior at the onset of the amber interval. The first method continuously checks, at each time step, whether the driver will decide to continue driving through the intersection or will stop at the stop line. The second method assigns to each driver "One Decision" that does not change until the vehicle crosses the stop line

(PTV Group, 2020). This one decision is based on a logistic regression function that represents the drivers' stop probability. The function uses three coefficients: Alpha (α), Beta1 (β1), and Beta2 (β2). The reaction-to-amber of the simulated drivers in VISSIM is a function of the values of these three coefficients along with the vehicle approach speed (v) and the distance to the stop bar at the onset of amber (dx). Equation 3-5 shows the utilized simulation probability function (p).

$$p = \frac{1}{1 + e^{-\alpha - \beta_1 v - \beta_2 dx}} \tag{3-5}$$

where,

p = probability that a vehicle will stop at an amber light,

α = first logistic coefficient,

β_1 = second logistic coefficient, and

β_2 = third logistic coefficient.

The three coefficients in Equation 3-5 significantly influence the probability of a driver making a Stop or a Go decision, and subsequently the likelihood of violating a red-light indication. According to the VISSIM User Manual (PTV Group, 2020), the software uses empirical default values for α, β1, and β2 of 1.59, -0.26, and 0.27, respectively.

The proposed method in this study involves fine-tuning the parameters of the amber-decision probability function presented in Equation 3-5 to replicate what is expected based on real-world data. First, a sensitivity analysis was conducted to determine the impacts of the coefficient values by varying the values of each of the three coefficients, one at a time within a specific range recommended in the literature, while setting the other two coefficients at their default values. Then, this study used logistic regression to identify the best combination of the three coefficients that accurately replicate the real-world drivers' decision-making behavior during amber. The variables affecting the stop decisions in the simulation model are shown in Figure 3-7. Appiah et al. (2013) used a range of the three coefficients (α, $\beta1$, and $\beta2$) to calibrate VISSIM in order to analyze the actuated advance warning system (AAW) operations at high-speed signalized intersections. The AAW is an infrastructure-based Red-light Running (RLR) warning system that relies on upstream advanced detectors and static alerts with the activation of beacons for warnings. The researchers used the following as acceptable ranges for the stop-probability coefficients in the simulation model:

α = [0.08, 3.10], $\beta1$ = [-0.50, 2.50] and $\beta2$ = [0.01, 0.50]. These ranges are used later as a starting point for the simulation model calibration that aims to find the best combination of the three probability coefficients.

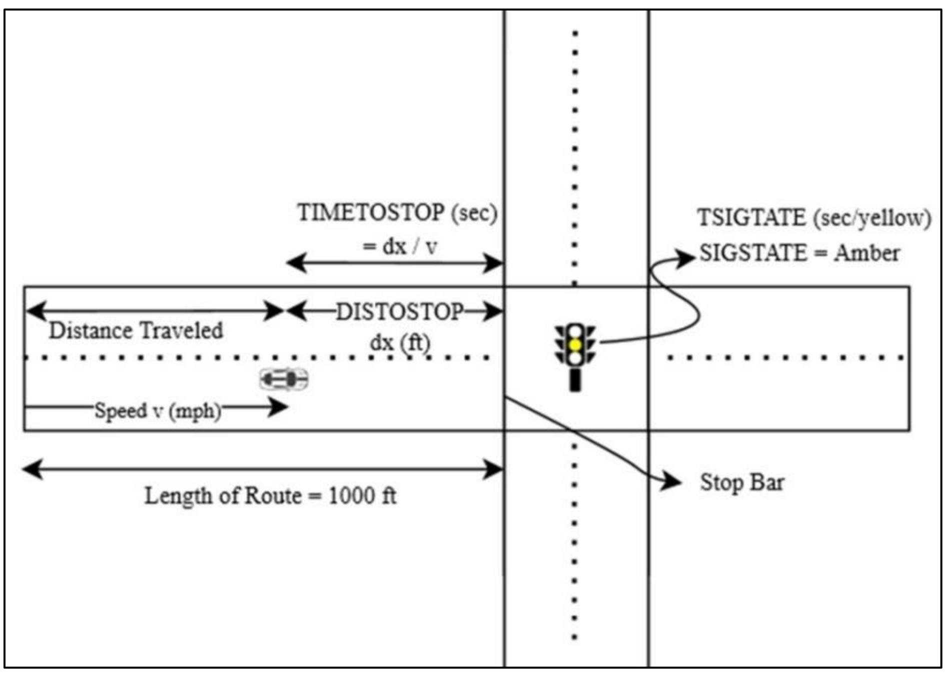

Figure 3-7: Variables Affecting the Stop Decisions in the Simulation Model

An algorithm is developed to analyze the vehicle trajectories output from the simulation models to determine whether the vehicle has made a Stop or a Go decision and/or violated the red-light in the simulation.

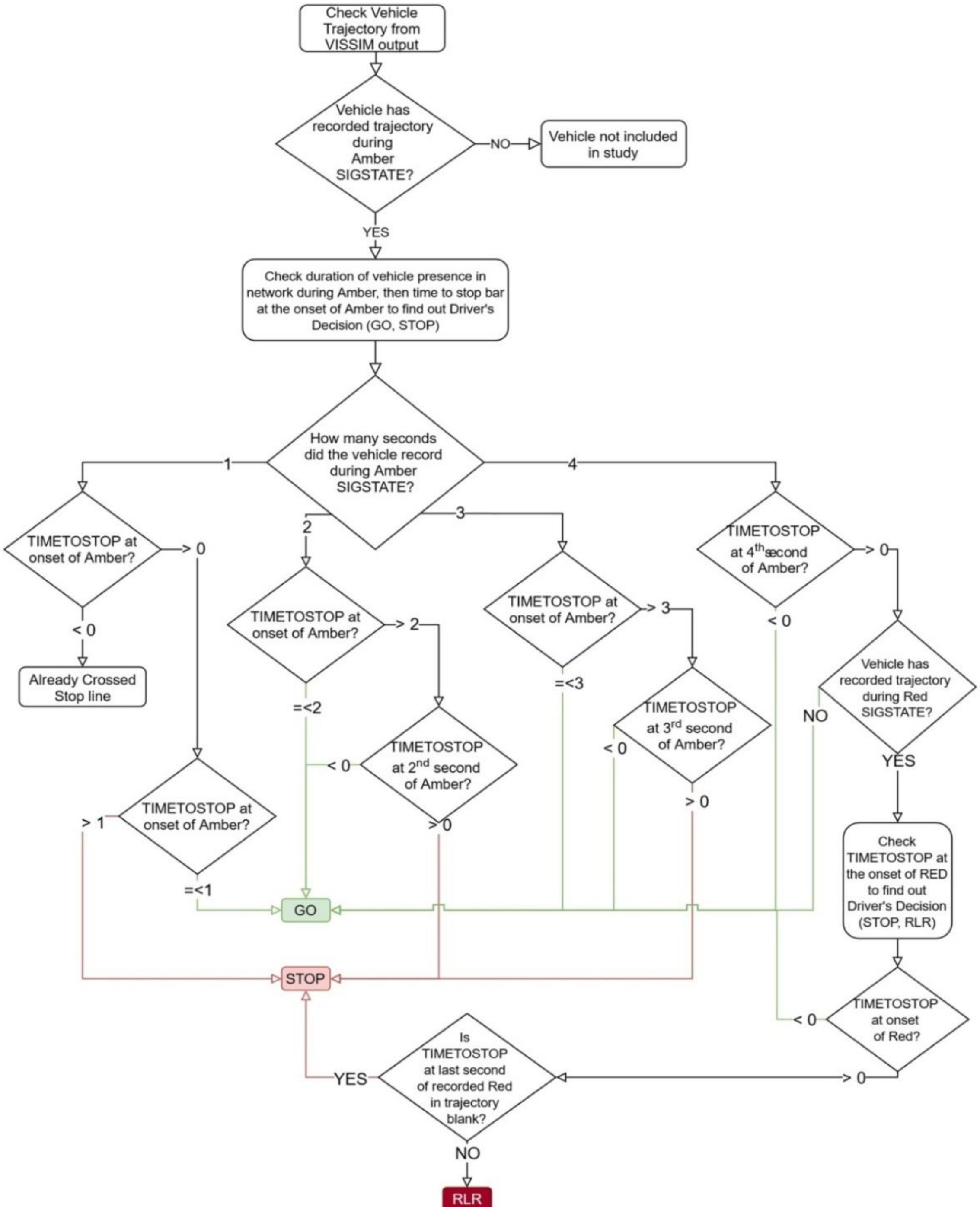

Figure 3-8: Vehicle Trajectories Analysis

As shown in Figure 3-7, the measures of interest that are calculated based on the vehicle trajectories from the simulation include the distance to stop bar (dx or DISTOSTOP) in feet (ft), time to stop bar (TIMETOSTOP) in seconds (sec), vehicle speed (v) in miles per hour (mph), signal status (SIGSTATE) and time of signal status (TSIGSTATE) in seconds (sec). SIGSTATE indicates the current status of the traffic signal (green, amber, or red) at each time step of the recorded trajectory. TSIGSTATE indicates how many seconds have passed during the current SIGSTATE.

The analysis flow shown in Figure 3-8 depends on TIMETOSTOP at the onset of yellow and on how many seconds the vehicle spent while the SIGSTATE was yellow. The modeled intersection has a yellow signal time of 4.0 seconds per cycle.

To decide whether the driver made a Stop or a Go decision or a red-light violation, the algorithm first looks at whether the vehicle has a recorded trajectory during the amber signal state or not. If the latter option is the case, the vehicle is not considered in the study as it would have arrived either during the green signal state and crossed the intersection, or during the red signal state. If the vehicle has recorded trajectory during the amber signal state, the algorithm then checks the duration of vehicle presence on the link, behind the stop bar, and during amber. Since the yellow signal interval is 4-seconds, there are four possible scenarios for the trajectories during this signal state;

1. The first scenario is considering a vehicle has one recorded trajectory: In this case, the algorithm then checks the TIMETOSTOP for two possibilities:
    a. TIMETOSTOP is negative indicating that the vehicle has already crossed the stop bar, during the last second of green, while the signal was just turning yellow. This vehicle is not further considered in the study (i.e., Already crossed the stop line).

b. TIMETOSTOP is positive, indicating two new conditions that the algorithm looks at next:

   i. TIMETOSTOP is less than one second implying that the signal turned yellow while the vehicle was very close to the stop bar. This vehicle made a GO decision because otherwise, it would have recorded more than one trajectory.

   ii. TIMETOSTOP is greater than one second implying that the vehicle has entered the network during the last (4^{th}) second of the amber signal state and made a STOP decision.

2. The second scenario is considering a vehicle has two recorded trajectories: The algorithm checks again the TIMETOSTOP at the onset of amber for two possibilities:

   a. TIMETOSTOP is less than or equal to two seconds implying that the signal turned yellow while the vehicle was very close to the stop bar and that it made a safe GO decision because otherwise, it would have recorded more than two trajectories.

   b. TIMETOSTOP is greater than two seconds which activates the algorithm to look for two new conditions in the second recorded trajectory, rather than the first recorded trajectory:

      i. TIMETOSTOP, in the second recorded trajectory of amber, is negative, indicating that the signal turned yellow while the vehicle was close to the stop bar, but not close enough to cross legally at its current speed. This implies that the vehicle accelerated and made a GO decision to cross the intersection during the 2^{nd} second of the yellow interval.

ii. TIMETOSTOP, in the second recorded trajectory of amber, is positive, indicating that the vehicle entered the network during the last two seconds of the amber signal state and made a STOP decision.

3. The third scenario is considering a vehicle has three recorded trajectories: The algorithm checks again the TIMETOSTOP at the onset of amber for two conditions similar to the possibilities (a) and (b) of the second scenario but with considering a TIMETOSTOP of 3 seconds instead of 2 seconds and the third recorded trajectory.
4. The fourth scenario is considering a vehicle that has four recorded trajectories: Since the length of the yellow phase is 4 seconds, this possibility implies that the vehicle could be anywhere on the VISSIM link when the signal turned yellow. This is why the algorithm looks directly at the TIMETOSTOP in the last record (4^{th} second) of the amber, rather than at the onset of amber, and checks the following two conditions:
   a. TIMETOSTOP is negative, indicating that the vehicle made a GO decision and crossed the intersection during the last second of amber.
   b. TIMETOSTOP is positive, indicating that the vehicle is still behind the stop bar during the last second of amber. The algorithm then checks if the vehicle recorded any trajectory during the following red phase:
      i. If the vehicle does not have a recorded trajectory during the red phase, this indicates that the TIMETOSTOP during the last second of amber was already very minimal and that the vehicle made a safe GO decision and crossed the intersection.
      ii. If the vehicle has recorded trajectory during the red phase, the algorithm is then activated to look at the TIMETOSTOP at the onset of Red for two possibilities:

1. TIMETOSTOP is negative, indicating that the vehicle made a safe GO decision and crossed the intersection in the last second of the amber.
2. TIMETOSTOP is positive which leads to two possible outcomes that the algorithm determines after looking at the TIMETOSTOP in the last recorded trajectory of the vehicle during the current red phase:
   a. TIMETOSTOP in the last trajectory is blank, which indicates that the speed is zero (mph) implying that the vehicle made a STOP decision and decelerated to a complete stop behind the stop bar.
   b. TIMETOSTOP is not blank which means that the speed is not zero (mph). This implies that the vehicle kept moving until it crossed the intersection and a red-light running violation occurred.

As developed by Gates et al. (2007), the drivers' probability of stopping and going in response to an amber signal can be written as a logistic model as shown in Equation 3-6, which is a binary function that represents the two responses of either Stop or Go.

$$\gamma = \ln\left[\frac{\pi_{go-thru}}{\pi_{stop}}\right] = 3.170 - 2.041x_{trav\ time(s)} + 0.044x_{speed(mph)} \tag{3-6}$$

$$\pi_{go-thru} = \frac{e^{\gamma}}{1+e^{\gamma}} \tag{3-7}$$

$$\pi_{stop} = 1 - (\pi_{go-thru}) \tag{3-8}$$

where

π_{stop} = probability of stopping in response to amber signal,

$\pi_{go\text{-}thru}$ = probability of going through the intersection in response to amber signal,

$x_{trav\ time(s)}$ = TIMETOSTOP (sec), and

$x_{speed(mph)}$ = vehicle speed (mph).

The simulation model calibration was done using logistic regression that aims to find the best combination of the three probability coefficients that result in the closest match between the drivers' simulated behavior (Equation 3-5) and real-world behavior (Equation 3-6). The study utilized the R Project for Statistical Computing tool to model both logistic regression functions (i.e., the simulation logit model and the real-world logit model). Several measures can be utilized in the calibration objective function such as minimizing the Sum Squared Error (SSE) or the Root Mean Squared Error (RMSE) between the model utilized in the simulation and the model developed based on real-world data by Gates et al., (2007). The SSE is used in this study as the calibration objective function. The SSE is the sum of the squared differences between each data point obtained from the simulation and its corresponding point resulting from the real-world model. To solve the calibration problem, the study utilized the Excel Solver that starts with a random combination of α, β1, and β2 and solves the problem under the specified constraints. The constraints that the objective function is subjected to are the coefficient ranges adopted from Appiah et al. (2013). Therefore, the calibration objective function can be written as shown in Equation 3-9;

$$SSE = \sum_{i=1}^{n} (p_i - p_{r_i})^2 \qquad (3\text{-}9)$$

Subject to:

$$\left.\begin{array}{l} 0.08 \le C_1 \le 3.10 \\ -0.50 \le C_2 \le -0.01 \\ 0.01 \le C_3 \le 0.50 \end{array}\right\} \text{ for each } i \text{ in } \{1, \dots, n\},$$

where

C_1, C_2, C_3 = calibration coefficients,

n = number of recorded trajectories during amber,

p_i = probability calculated using Equation 3-5 for i^{th} trajectory,

p_r = real-world probability calculated using Equation 3-6 and Equation 3-7, corresponding to the same i^{th} trajectory.

3.6.2 CV-based RLVW Modeling

The simulation model, calibrated as described above, was used to analyze the impact of CV-based RLVW on traffic safety at signalized intersections. The simulation of the RLVW application requires emulating CV alerts of the potential running of a red-light. CV-equipped vehicles that receive and utilize these messages were coded as an additional vehicle class in the simulation model. The simulation is done with a varying RLVW utilization rate that is defined as the multiplication of the CV market penetration rate and the percentage of positive response to the RLVW alerts among the CV drivers (Hadi et al., 2021). The RLVW algorithm utilized in the simulation environment is based on the concept of operation and the system requirements developed by the Federal Highway Administration (FHWA) for the RLVW CV-based application (Stephens et al., 2015). With this concept, the RLVW integrates data from the RSE utilizing SPaT and MAP messages and OBE applications to assess the potential for red-light running. The on-board application notifies the drivers when they need to decelerate to come to a complete stop and avoid a red-light violation.

3.7 Investigation of RLVW Impacts and Performance

The NTCIP "Vehicle Detector Extend Parameter" was used, as described earlier, to model the provision of the AGP to support accurate SPaT messages for the RLVW application. Given that the signal controller is programmed to rest-in-green on the major movement (the main street through movement), there are two possible scenarios for the

CV-based RLVW operation. The first scenario is when the phase of the major movement is in green, and there is no conflict call on the cross street (i.e., the signal controller is not terminating the major street phase). In this case, there will be no action required from the RSE. The second scenario is when having a conflicting call on the cross street and the major movement currently in green is about to be terminated. In this case, the controller will place an assured green extension for CV RLVW-equipped vehicles that are detected in the RLVW detection zone.

The RLVW application on the OBE receives and utilizes SPaT messages with the AGP calculated and implemented by the RSE. It should be noted that the AGP is modeled assuming that the market penetration rate is equal to the utilization rate, meaning that all vehicles are assumed to utilize the provided RLVW. This assumption can be varied depending on the purpose of the study.

As the simulated CV approaches the signalized intersection, it continuously obtains the current traffic signal status through SPaT messages, if they are within the communication range. If the CVs are detected in the RLVW detection zone, the controller will place an assured extension for the green time. This green extension when added to the yellow interval and all-red interval allows the vehicle to clear the intersection safely and eliminate the potential of running a red light. In addition, it provides definitive times for CVs with accurate information as to when the green interval will end. A C# program was written to send SNMP packets carrying the Vehicle Detector Extend Parameter to the controller in a tenth of a second using the corresponding NTCIP OID. In addition, if the remaining green time is less than the AGP or the current signal is yellow and it is determined that these vehicles cannot clear the intersection safely within the assured extended green time, the vehicle will receive a warning message indicating the potential of a red-light violation. The on-board application notifies the drivers when they need to decelerate to come to a complete stop and avoid a red-light violation.

The study developed an algorithm to analyze the vehicle trajectories output from the simulation models to count the number of vehicles that violate the red-light in the simulation. The variables of interest obtained from each simulation for use in the investigation include vehicle speed, the distance to the stop line, and the remaining time to the end of the current signal state, which indicates how many seconds have passed during the current signal phase. First, the impact of the AGP on the performance of the RLVW application is investigated under moderate traffic demands. Then, two additional scenarios with increased traffic demand (10% and 20%) are analyzed to investigate the impact of AGP with different traffic demands.

The benefits of the RLVW are assessed under pre-timed signal control and semi-actuated signal control in terms of safety and mobility. The safety performance measures of the RLVW are quantified based on the SSAM tool developed by the FHWA using the extracted vehicle trajectories from the simulation. The SSAM is a tool that estimates the safety of traffic facilities by analyzing the traffic conflicts which is then converted to Surrogate Safety Measures (SSM). This study utilizes the Time-To-Collision (TTC) and Post-Encroachment Time (PET), which are two surrogate measures defining the conflict between two vehicles using the specified threshold values (Hadi et al., 2019). The threshold values of the TTC and PET used in the analysis are 1.5 seconds and 5.0 seconds, respectively, which are the default values in the SSAM. The mobility measures include the stopped delay, approach delay, and the number of stops.

3.8 Summary

This chapter discussed the methodologies and the application steps that were adopted in the dissertation. A case study was developed to simulate the CV-based RLVW under pre-timed and semi-actuated signal control using EILS, SILS, and HILS platforms. An actuated signal controller support of RLVW was implemented in the HILS and described in detail. In addition, this chapter described the data flow between the HILS hardware and software components, the simulation network calibration, the CV-based RLVW modeling, and the methodology used for the investigation of the RLVW impacts.

CHAPTER 4
ANALYSIS AND RESULTS

This chapter presents and discusses the results from the application and analysis of the proposed methodology described in Chapter 3. An important focus of this chapter is the evaluation of the impacts of the RLVW application under pre-timed and semi-actuated signal operations based on mobility and safety performance measures. First, the chapter presents the results of the VISSIM simulation model calibration and validation. In addition, the chapter compares the results of the assessment of the RLVW when using the EILS, SILS, and HILS approaches for signal timing control simulation. The comparison of the three approaches is done based on communication delay, signal timing measures, and safety performance measures. Moreover, the chapter describes the impacts of the RLVW application on mobility and safety for the case study signalized intersection using simulation under pre-timed and semi-actuated signal operations.

Each data point reported from the simulation is the average of the outputs from ten simulation model runs, each with different seed numbers, to account for the stochasticity of the microscopic simulation model. The simulation was carried out for 70 minutes (10 minutes of warm-up and 1 hour of evaluation time). For the modeled case study intersection, the maximum communication range was assumed to be 1,000 ft, according to the 5.9 GHz dedicated short-range communication (DSRC) operational concept and technology requirements. The broadcast reception range for an On-board Unit is typically 1,100 ft at a standard roadside unit (IEEE, 2021). Please, note that the application may be implemented using C-V2X communication technology and the communication range can be updated based on the utilized communication technology capability. The perception-reaction time is assumed to be 1.5 seconds according to the standards of the American

Association of State Highway and Transportation Officials (AASHTO) to allow 1 second for perception time and 0.5 second for reaction time. The following sections elaborate on the results of the efforts that were undertaken in this research.

4.1 Model Calibration Results

The sensitivity analysis of the impacts of the values of the three coefficients of Equation 3-5 showed that the α parameter had a minor effect on the Stop or Go decisions and RLR events in the simulation. However, the $\beta 1$ and $\beta 2$ were positively correlated with the number of stop-decisions and negatively correlated with the number of go-decisions. Moreover, $\beta 1$ and $\beta 2$ were negatively correlated with the number of RLR violations. This means that the higher is the values of $\beta 1$ and $\beta 2$, the higher is the likelihood of a vehicle stopping on amber and the lower chances of running a red-light.

Figure 4-1 shows the probability of stopping resulting from the simulation model with different logistic regression coefficients compared to the results expected based on the model derived using real-world drivers' behavior.

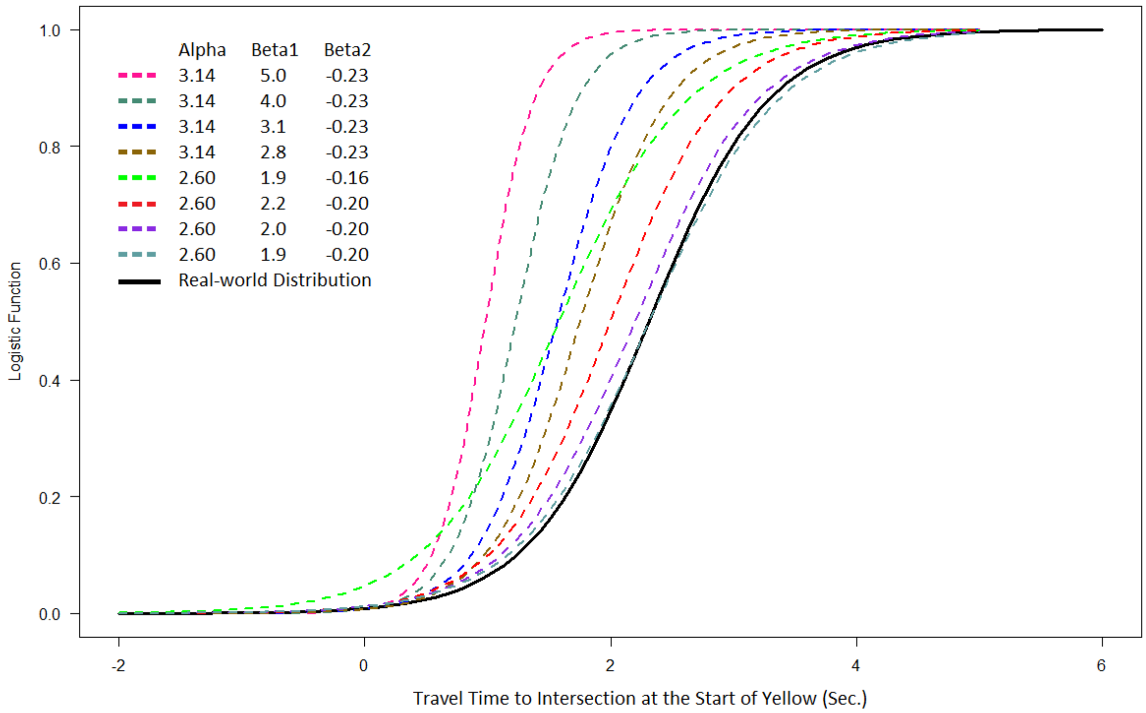

Figure 4-1: Simulation versus Real-world Probability of Stopping

Results from the logistic regression showed that the combination of $\alpha = 2.60$, $\beta1 = 1.90$, and $\beta2 = -0.20$ was able to minimize the SSE.

4.2 Communication Delay and Latencies

The results obtained for the case study of this dissertation reveal some of the operational differences due to using different signal controller methods in the simulation. With the EILS, at each simulation time step, the traffic simulator sends the virtual detector calls to the internal emulator, which returns the signal state for the next time step, almost instantaneously. This means that there is almost no communication latency between the RBC emulator and the traffic simulator. On the other hand, the SILS and HILS methods involve additional latency in transferring the information. The SILS includes a virtual Traffic Control Kernel along with the Dynamic Link Library that is responsible for sending the detector calls to the simulated ASC/3 controllers and receiving back the signal status information. The HILS integrates a physical traffic signal controller that receives the virtual detector calls from the simulation and sends back the signal states through the utilized middleware. The communication mechanism between the controller and the simulator in both the SILS and the HILS platforms introduces delay and latency in transferring the information.

To further confirm, the communication delay is measured in milliseconds (Msec) and quantified for both SILS and HILS platforms using two measures: “Get Phase Status Duration” and “Processing Time”. The Get Phase Status Duration is defined as the time required by the middleware to get the signal state from the traffic signal controller. The Processing Time is defined as the time required by the middleware for processing the signal state and the detector status. Both measures are quantified in the HILS platform using the communication delay log files generated by the middleware. Another computer program is written in the C# language to collect the same information and measure the latency in the ASC/3 controller in the SILS platform.

For analysis purposes, a total of 1050 events of “Get Phase Status Durations” and “Processing Times” are collected for the SILS and HILS platforms to compare the latencies introduced in these two platforms. The results show that the average time intervals that are required to read the signal state from the ASC/3 controller in the SILS platform and from the Cobalt G-series controller are 30 milliseconds and 29.11 milliseconds, respectively. In addition, the average time intervals that are required for processing the detector information to the ASC/3 controller and the Cobalt G-series controller are 506.64 milliseconds and 516.49 milliseconds, respectively. The average communication delays, latencies in transferring the information, and processing the information between the signal controller and the detector actuations in the SILS and HILS platforms are quite similar on average.

4.3 Signal Timing Measures of Effectiveness

The signal timing measures are the second category of measures investigated in this dissertation to test the consistency of the phase calls/actuations across the EILS, SILS, and HILS platforms. Figure 4-2 indicates that the EILS provides different results compared to the SILS and the HILS, but the SILS and HILS provide similar results. The average green times for the left-turn movements and side-street movements in the EILS are higher than those in the SILS and HILS. In addition, the average numbers of occurrences of the phases for all signal groups in the EILS are lower than those in the SILS and HILS. These two observations are related in that the provision of more green time per phase in the EILS increases the probability of skipping phases thus reducing the number of phase occurrences. The lower latency in detecting the vehicles by the control system in the ELIS increases the probability of extending the green for a detected vehicle compared to the SILS and HLIS.

The almost immediate controller/simulator communication in the EILS platform allows a higher number of vehicles to place and extend the detector calls in a phase, resulting in longer green intervals and fewer phase repetitions. On the other hand, the communication delays introduced in the SILS and HILS may result in more vehicles not being served in the same phase as they arrive. This latency leads to shorter green intervals and a higher number of phase occurrences.

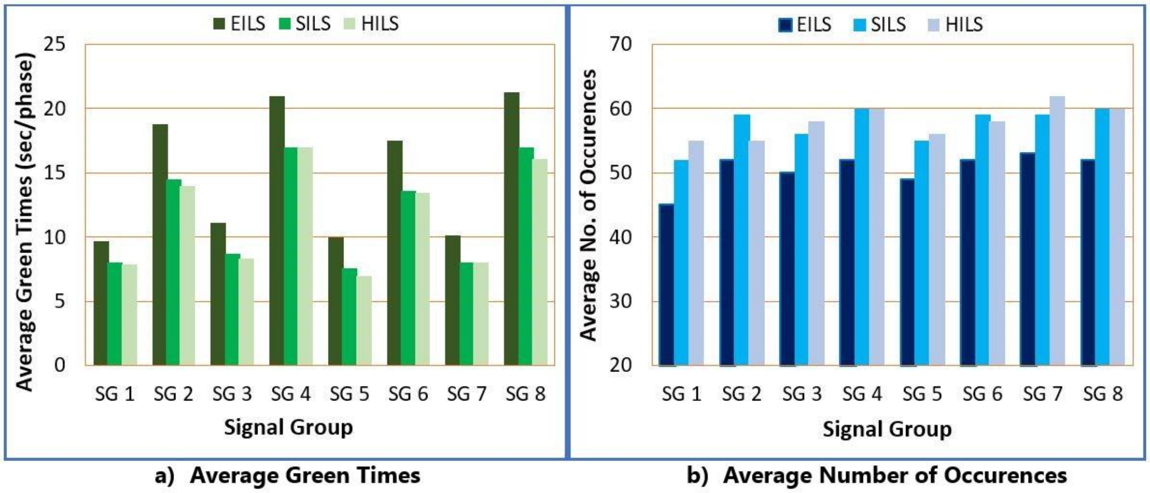

Figure 4-2: Signal timing MOEs results

4.4 Safety Enhancement Assessment Using EILS, SILS, and HILS

This study evaluated the impact of using the three different simulation platforms and methods of modeling traffic signal control on the assessed safety enhancement due to the RLVW application. The utilized SSAM measures in the assessment are related to the right-angle conflicts and rear-end conflicts, which are the main types of conflicts associated with RLR. This evaluation was done only for the through-movements on the main street. The evaluation of the safety benefits of the RLVW application uses the average of the outputs from ten simulation model runs, each with different seed numbers, to account for the stochasticity of the microscopic simulation model. The CV-based RLVW application was tested under pre-timed signal control operation and semi-actuated signal control operation. Table 4-1 shows the impacts of the examined simulation platform on the safety performance of the RLVW application in the case of pre-timed signal control in terms of the number of red-light running and the total number of conflicts. The results show that for pre-timed signal operation, the utilized simulation platform does not have a significant impact on the modeled CV-based RLVW application.

Table 4-1: RLVW under Pre-timed Signal Control

Pre-timed Signal Control									
UR	EILS			SILS			HILS		
	RLR	SSAM Conflicts		RLR	SSAM Conflicts		RLR	SSAM Conflicts	
		Right angle	Rear-end		Right angle	Rear-end		Right angle	Rear-end
0%	6.7	5.1	10	7.0	4.4	8	6.0	3.8	8
10%	7.1	5.4	40	6.7	5.0	38	5.0	6.0	39
20%	6.3	5.3	60	6.0	4.6	68	6.0	5.0	54
30%	5.6	6.8	64	5.6	5.6	68	5.0	4.5	65
40%	4.3	6.0	61	3.5	4.8	60	3.0	4.5	62
50%	3.6	4.8	60	2.6	4.4	60	2.0	4.0	65
60%	3.2	5.3	59	2.8	4.4	58	2.0	4.0	65
70%	3.9	4.7	45	3.2	4.0	43	3.0	4.0	44
80%	3.4	3.7	33	3.1	3.6	37	3.0	3.0	35
90%	2.3	3.5	18	1.9	3.4	20	1.0	2.5	23
100%	0.9	2.8	1	1.0	2.8	3	0.8	1.0	1

In general, Table 4-1 shows that at utilization rates below 30%, the number of conflicts increases as the RLVW utilization rate increases with pre-timed control. This is the result of the large probability of connected vehicles, being followed by conventional vehicles that do not have access to the RLVW information. At rates higher than 30%, there will be a higher chance of two or more connected vehicles following each other and the number of conflicts starts to decrease further to reach one conflict per hour for the EILS and HILS, and three conflicts per hour for the SILS at 100% utilization. The inconsistent initialization of the signal controller in the three platforms, as previously reported in the review of literature, might be the reason for introducing the minor differences in the results mentioned above.

Table 4-2 shows the impacts of the examined simulation platforms on the safety performance of the RLVW application in the case of semi-actuated signal control operation. In general, the SILS and HILS platforms provided a higher number of red-light running events, right-angle conflicts, and rear-end conflicts compared to the EILS and this is because the number of phase occurrences in the SILS and the HILS is higher than the EILS, which increase the probability of having higher numbers of RLR violations.

Table 4-2: RLVW under Semi-actuated Signal Control

Semi-actuated Signal Control									
UR	**EILS**			**SILS**			**HILS**		
	RLR	**SSAM Conflicts**		**RLR**	**SSAM Conflicts**		**RLR**	**SSAM Conflicts**	
		Right angle	Rear-end		Right angle	Rear-end		Right angle	Rear-end
0%	7.1	6.4	13	8.0	8.0	9	8.0	9.3	10
10%	6.9	4.3	25	7.9	8.5	37	7.9	10.0	42
20%	6.8	5.3	45	7.9	9.0	54	7.9	11.0	61
30%	6.8	5.3	50	7.3	9.5	65	7.3	11.5	78
40%	7.3	4.7	50	7.2	4.5	77	7.2	8.0	80
50%	6.5	3.0	58	5.8	6.0	76	5.8	7.0	79
60%	6.3	4.7	54	6.1	7.0	72	6.1	5.4	75
70%	6.9	5.7	43	7.4	5.0	54	7.4	7.0	61
80%	6.8	5.0	27	7.9	8.0	44	7.9	7.0	52
90%	6.2	3.0	20	7.0	7.0	21	7.0	8.0	25
100%	4.0	5.7	2	6.8	9.0	2	6.8	9.0	3

In comparing the differences between the three platforms under semi-actuated signal control operation, the results show that the differences are higher with the SILS and HILS compared to the differences with pre-timed signal control.

It is interesting from comparing the results in Tables 4-1 and 4-2 that the number of red-light running events is clearly higher under semi-actuated signal control compared to those with pre-timed signal control operation. For example, the differences between the pre-timed signal control and semi-actuated signal control in terms of the number of red-light running ranged from 6% to 60% (0.2 to 3 RLR per hour) in the case of EILS and ranged from 13% to 82% (1.0 to 5.6 RLR per hour) in the case of SILS. The differences ranged from 25% to 86% (2.0 to 6.0 RLR per hour) in the case of HILS.

The reason for these differences is that the end-of-green intervals for the main street through movements depend on the gap out of the subject approach. Thus, with an actuated traffic signal operation, the CV-based RLVW application lacks the input information about when exactly the green interval is going to be terminated to the next phase.

In summary, the simulation results show that the RLVW application was able to successfully reduce the RLR events by approximately 90% by increasing the CV utilization rate from 0% to 100% in the case of pre-timed signal control. However, in the case of semi-actuated signal control, the RLVW algorithm was able to reduce the RLR events by only 26.7% according to the EILS, 15% according to the SILS, and 12.5% according to the HILS with increasing the CV utilization rate from 0% to 100%.

4.5 RLVW Safety Measures Assessment Under HILS

In order to quantify the impact of traffic signal operations (i.e., pre-timed and semi-actuated) on the performance of the RLVW and to provide a solution for the end-of-green uncertainties associated with the semi-actuated operations, the dissertation focused only on the HILS results in the next sections. The utilized safety performance measures are the total number of red-light running events and safety surrogate measures produced by the SSAM tool. The utilized SSAM measures are related to the right-angle and the rear-end conflicts, which are the types of conflicts associated with RLR. In this study, the RLVW application is only evaluated for the through-movement vehicles on the main street. The CV-based RLVW application was tested under pre-timed signal control operation and semi-actuated signal control operation. The results are shown in the following subsections.

4.5.1 Safety Assessment under Pre-timed Signal Control

The simulation model, calibrated as described above, was used to analyze the impact of CV-based RLVW on traffic safety at signalized intersections under pre-timed control. Table 4-1 shows the impacts of the examined simulation platform on the safety performance of the RLVW application in the case of pre-timed signal control in terms of the number of red-light running and the total number of conflicts. The results show that the number of RLR decreased from 6 vehicles per hour to 0.8 vehicles per hour when the utilization increased from 0% to 100%. In addition, the number of rear-end conflicts decreased from 65 conflicts per hour to 1 conflict per hour with increasing the utilization rate of RLVW from 30% to 100%. In addition, the right-angle conflicts decreased from 6.0 conflicts to 1 conflict per hour with increasing the utilization rate of RLVW from 10% to 100%. In general, for pre-timed signal operation, at utilization rates below 30%, the results showed that the number of conflicts increases as the RLVW utilization rate increases.

4.5.2 Safety Assessment under Semi-actuated Signal Control

Table 4-2 shows that the numbers of RLR fluctuate between 8.0 vehicles per hour and 6.0 vehicles per hour when the utilization increased from 0% to 100%. In addition, the number of rear-end conflicts fluctuate between 80 conflicts per hour and 25 conflicts per hour with increasing the utilization rate of RLVW from 0% to 100%. In addition, the right-angle conflicts fluctuate between 11.5 conflicts and 5.3 conflicts per hour with increasing the utilization rate of RLVW from 0% to 100%. As with the pre-timed signal control, for semi-actuated signal operation and utilization rates below 30%, the results showed that the number of conflicts increases as the RLVW utilization rate increases. This is the result of the large probability of connected vehicles, being followed by conventional vehicles that do not have access to the RLVW information. At rates higher than 30%, there is a higher chance of two or more connected vehicles following each other and the number of conflicts starts to decrease further to reach one conflict per hour.

By comparing the results in Tables 4-1 and 4-2, the number of red-light running events is clearly higher under semi-actuated signal control compared to those with pre-timed signal control operation. For example, the differences between the pre-timed signal control and semi-actuated signal control in terms of the number of red-light running ranged from 25% to 86% (2.0 to 6.0 RLR per hour). In addition, the differences between the pre-timed signal control and semi-actuated signal control in terms of the number of right-angle conflicts ranged from 8.0 to 0.8 conflicts per hour. Moreover, the differences between the pre-timed signal control and semi-actuated signal control in terms of the number of rear-end conflicts ranged from 18 to 2 conflicts per hour.

4.5.3 AGP Support Results for RLVW Application under Actuated Signal Controller

This section is divided into two main sections. First, the assessed impacts of the AGP on the performance of the RLVW application are presented under moderate traffic demands in section 4.5.3.1. Then, two additional scenarios with increased traffic demand (10% and 20%) are presented in section 4.5.3.2. Based on utilizing the 85th percentile vehicle speed the distance required for bringing vehicles to a complete stop is 393.75 feet and the time required to clear the modeled intersection is 2.0 seconds. In addition, the time to travel through the stopping distance is 5.25 seconds. According to Equation 3-4, the results show that the RLVW critical time is 7.75 seconds. By subtracting the yellow interval from the RLVW critical time, the AGP is calculated to be 2.95 seconds to provide sufficient time for vehicles to cross the intersection safely without violating the red-light.

4.5.3.1 AGP Support Results with Moderate Traffic Demands

Figure 4-3 shows the total number of red-light running events with and without applying the AGP with RLVW utilization rates ranging from 0% to 100%. The results show that without utilizing the AGP, the total number of RLR decreased from 8.0 to 5.8 events per hour when the RLVW utilization rate increased from 0% to 100% providing only a 27% improvement in safety. The decrease in the RLR with the utilization rate increase was not continuous and fluctuated as the rate increased, as shown in Figure 4-3. On the other hand, the results of applying the AGP in Figure 4-3 show a clear decreasing trend in the number of RLR events. The total number of RLR decreased from 8.3 to 0.7 events per hour with increasing the CV utilization rate from 0% to 100%. It can be inferred from Figure 4-3 that the AGP is able to improve the performance of the RLVW application under semi-actuated signal control and reduce the red-light running events by approximately 92%.

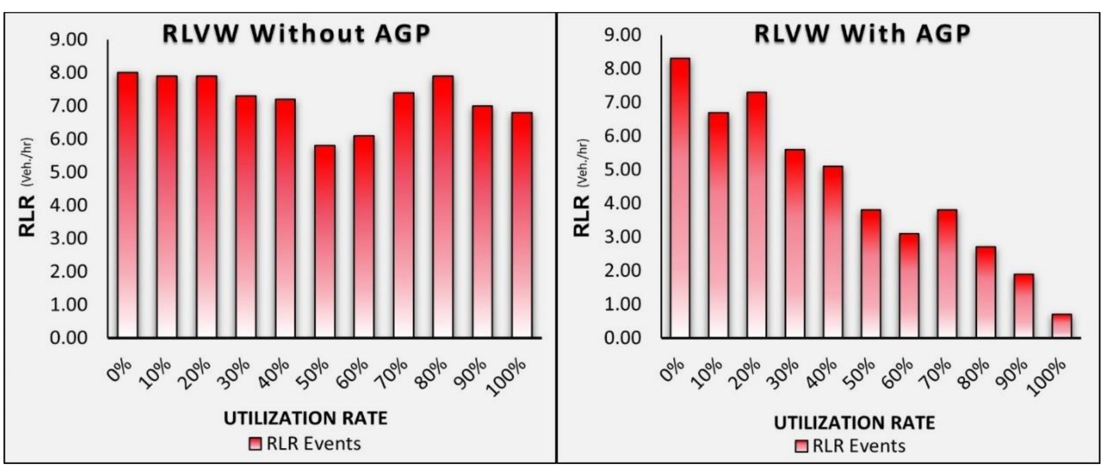

Figure 4-3 Impacts of the AGP on the Number of Red-Light Running Events

In terms of the surrogate safety measures obtained based on the SSAM assessment, Figure 4-4 shows the number of right-angle and rear-end conflicts with and without applying the AGP and with RLVW utilization rates ranging from 0% to 100%. The results show that without utilizing the AGP, the total number of right-angle conflicts fluctuates between 11.5 and 5.4 conflicts per hour when the RLVW utilization rate increases from 0% to 100%. However, with applying the AGP, there is a clear decreasing trend in the number of right-angle conflicts. The total number of right-angle conflicts decreased from 9.3 to 0.5 conflicts per hour with increasing the CV utilization rate from 0% to 100%.

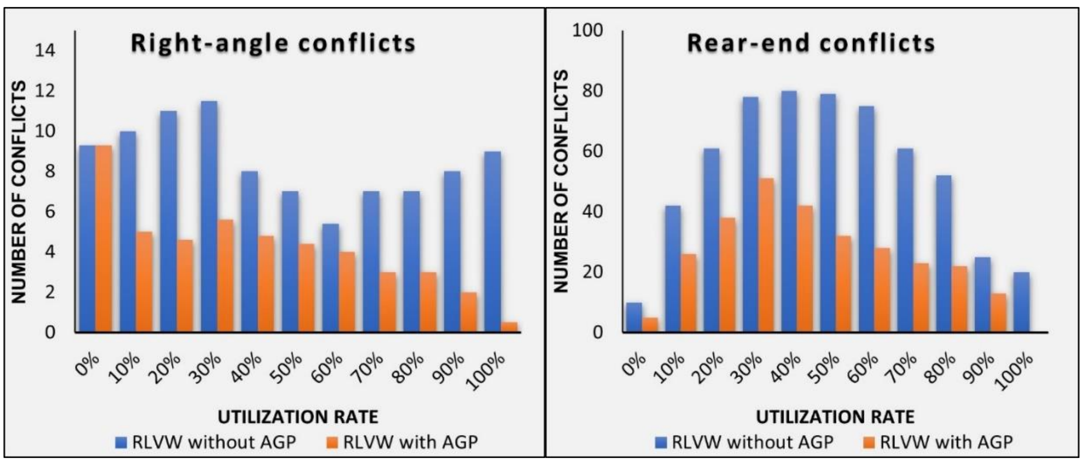

Figure 4-4 Surrogate Safety Assessment vs Mobility Benefits for the RLVW

Regarding the rear-end conflicts, the results in Figure 4-4 showed that the number of conflicts increased with the increase in the RLVW utilization rate up to a utilization rate of 40%, reaching 80 conflicts per hour without utilizing the AGP and 42 conflicts per hour with utilizing the AGP. This is the result of the large probability of connected vehicles, being followed by conventional vehicles that do not have access to the RLVW information. At rates higher than 40%, there will be a higher chance of two or more connected vehicles following each other. Hence, the number of rear-end conflicts started to decrease. As the utilization rate increases further, the rear-end conflicts continue to drop and decrease from

80 to 20 conflicts per hour with increasing the utilization rate of RLVW from 40% to 100%, without utilizing the AGP. While the rear-end conflicts decrease from 42 to zero conflicts per hour with increasing the utilization rate of RLVW from 40% to 100%, with the AGP.

4.5.3.1 AGP Support Results with 10% and 20% Increase in Traffic Demands

Figure 4-5 shows the total number of red-light running events with and without applying the AGP with a 10% increase in traffic demands and RLVW utilization rates ranging from 0% to 100%. The results show that without utilizing the AGP, the total number of RLR fluctuates between 9.7 to 2.9 events per hour when the RLVW utilization rate increases from 0% to 100%. As shown in Figure 4-5, although the decrease in the RLR with the increase in the utilization rate was not continuous, the trend is less fluctuated compared to the results in the scenario with moderate traffic demands, discussed in the previous section. On the other hand, the results with applying the AGP in Figure 4-5 shows a clear decreasing trend in the number of RLR events. The total number of RLR decreased from 8.7 to 2.2 events per hour with increasing the CV utilization rate from 0% to 100%.

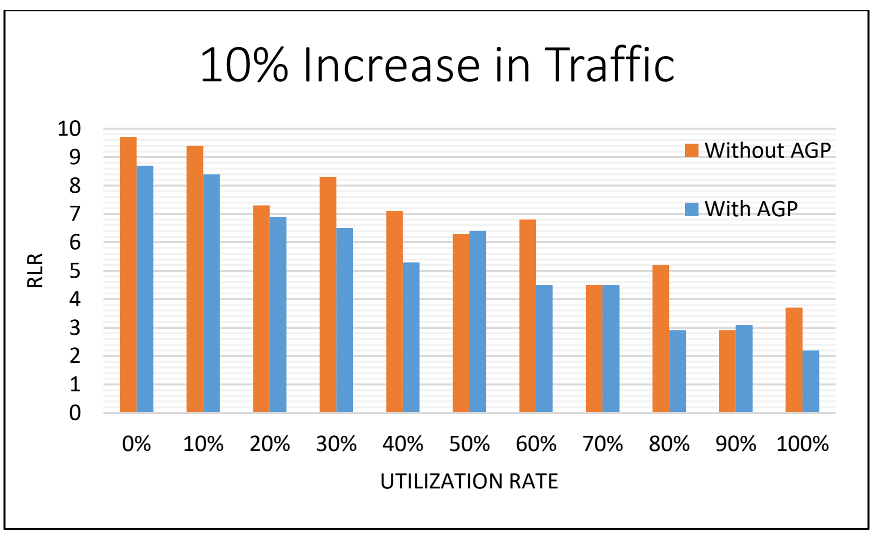

Figure 4-5 Impacts of the AGP on RLR with 10% Increase in Traffic Demands

Figure 4-6 shows the total number of red-light running events with and without applying the AGP with a 20% increase in traffic demands and RLVW utilization rates ranging from 0% to 100%. The results show that without utilizing the AGP, there is a clear decreasing trend in the total number of RLR between 8.7 to 1.6 events per hour when the RLVW utilization rate increased from 0% to 100%. The decrease in the RLR was more continuous with the increased utilization rate compared to the previous scenarios with moderate traffic demands and a 10% increase in traffic demands. On the other hand, the results with applying the AGP in Figure 4-6 shows a similar decreasing trend in the number of RLR events compared to the previous scenarios with the moderate traffic demands and a 10% increase in traffic demands. The total number of RLR decreased from 8.5 to 1.3 events per hour with increasing the CV utilization rate from 0% to 100%.

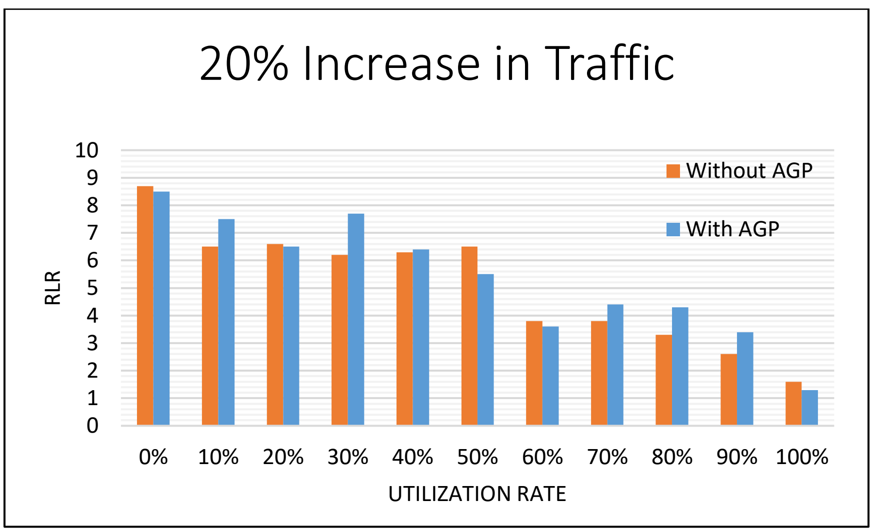

Figure 4-6 Impacts of the AGP on RLR with a 20% Increase in Traffic Demands

By comparing the results in Figures 4-3, 4-5, and 4-6, it can be inferred that the RLVW application was able to provide fewer false alarms due to the uncertainties in the end-of-green intervals with increasing the traffic demand by 10% and 20% compared to the moderate traffic scenario. In the cases of a 10% and 20% increase in traffic demands, the chances that the phases reach their maximum values (Max Out) increase with higher demands, allowing the provision of more accurate SPaT messages. The underlying algorithm on the OBE on the CV can then use this information to perform the required calculations and send alerts and warnings to drivers based on the received SPaT information. However, in the case of moderate traffic demands and low traffic demand, the chances that the signal phases terminate before the maximum green time is reached (Gap Out) increase, which results in higher varying ends of the green time between cycles and affects the functionality and performance of the applications.

Tables 4-3 to 4-5 show the results of two-tail t-tests to investigate if the changes in the means of the RLR values due to AGP with different utilization rates are significantly different at the 95% significance level for the three demand scenarios respectively, (i.e., moderate traffic), 10% increase in traffic, and 20% increase in traffic, respectively. If the P-values are significant at the 95% confidence level, they are denoted with *, **, *** for the base case, 10% increase in traffic, and 20% increase in traffic in the tables, respectively.

The results in Table 4-3 shows that for the base case scenario (i.e., moderate traffic demands), the t-test results for CV utilization rates above 30% show strong evidence against the null hypothesis, and it can be concluded that the RLR is significantly different with AGP. Regarding the 10% increase in traffic demands scenario, Table 4-4 shows that except for CV utilization rates of 80% and 100%, the t-test results failed to reject the null hypothesis, and it can be concluded that there is no significant difference between the number of RLR events with and without applying the AGP. Finally, regarding the 20% increase in traffic demands scenario, the t-test results failed to reject the null hypothesis, and it can be concluded that there is no significant difference between the number of RLR events with and without applying the AGP. The results show that the AGP has a significant impact on reducing the RLR events in the case of moderate traffic scenarios but not in congested traffic conditions.

Table 4-3: T-test Results for Moderate Traffic Demands Scenario with Different Utilization Rates (UR)

Statistic Measure	UR 0%		UR 10%		UR 20%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	8.0	8.3	7.9	6.7	7.9	7.3
Variance	9.33	2.01	14.1	2.46	16.5	0.68
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	-0.2515		0.9126		0.4215	
P(T<=t) two-tail	0.8071		0.3852		0.6833	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 30%		UR 40%		UR 50%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	7.3	5.6	7.2	5.1	5.8	3.8
Variance	17.79	1.38	9.51	1.43	5.96	0.62
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	1.3077		2.5120		2.5820	
P(T<=t) two-tail	0.2234		0.0332*		0.0296*	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 60%		UR 70%		UR 80%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	6.1	3.1	7.4	3.8	7.9	2.7
Variance	5.66	0.99	2.49	3.73	3.66	2.01
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	3.4017		5.1255		7.4710	
P(T<=t) two-tail	0.0079*		0.0006*		0.0001*	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 90%		UR 100%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*
Mean	7	1.9	6.8	0.7
Variance	3.33	2.32	5.29	0.68
Observations	10	10	10	10
df	9		9	
t Stat	6.3043		7.1834	
P(T<=t) two-tail	0.0001*		0.0001*	
t Critical two-tail	2.2622		2.2622	

Table 4-4: T-test Results for 10% Increase in Traffic Demands Scenario with Different Utilization Rates (UR)

Statistic Measure	UR 0%		UR 10%		UR 20%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	9.7	8.7	9.4	8.4	7.3	6.9
Variance	12.01	18.46	5.38	10.04	7.12	5.88
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	0.6610		0.9214		0.3906	
P(T<=t) two-tail	0.5252		0.3809		0.7052	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 30%		UR 40%		UR 50%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	8.3	6.5	7.1	5.3	6.3	6.4
Variance	8.01	8.06	6.10	3.12	4.68	6.04
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	1.5360		1.9140		-0.1357	
P(T<=t) two-tail	0.1589		0.0879		0.8951	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 60%		UR 70%		UR 80%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	6.8	4.5	4.5	4.5	5.2	2.9
Variance	7.73	6.06	3.83	3.83	4.62	1.88
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	1.9431		0.0000		2.6838	
P(T<=t) two-tail	0.0839		1.0000		0.0251**	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 90%		UR 100%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*
Mean	2.9	3.1	3.7	2.2
Variance	3.43	4.32	3.34	1.07
Observations	10	10	10	10
df	9		9	
t Stat	-0.2242		2.2934	
P(T<=t) two-tail	0.8276		0.0475**	
t Critical two-tail	2.2622		2.2622	

Table 4-5: T-test Results for 20% Increase in Traffic Demands Scenario with Different Utilization Rates (UR)

Statistic Measure	UR 0%		UR 10%		UR 20%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	8.7	8.5	6.5	7.5	6.6	6.5
Variance	18.46	6.06	6.72	2.72	8.04	3.17
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	0.1263		-1.0742		0.0849	
P(T<=t) two-tail	0.9023		0.3107		0.9342	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 30%		UR 40%		UR 50%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	6.2	7.7	6.3	6.4	6.5	5.5
Variance	8.40	8.23	11.12	4.93	8.06	2.06
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	-1.0310		-0.0842		0.9891	
P(T<=t) two-tail	0.3294		0.9347		0.3485	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 60%		UR 70%		UR 80%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*	*Without AGP*	*With AGP*
Mean	3.8	3.6	3.8	4.4	3.3	4.3
Variance	1.96	2.04	3.07	2.27	2.68	3.57
Observations	10	10	10	10	10	10
df	9		9		9	
t Stat	0.2694		-1.2027		-1.2457	
P(T<=t) two-tail	0.7937		0.2598		0.2443	
t Critical two-tail	2.2622		2.2622		2.2622	

Statistic Measure	UR 90%		UR 100%	
	Without AGP	*With AGP*	*Without AGP*	*With AGP*
Mean	2.6	3.4	1.6	1.3
Variance	5.38	2.04	1.38	1.57
Observations	10	10	10	10
df	9		9	
t Stat	-1.0366		0.5369	
P(T<=t) two-tail	0.3270		0.6044	
t Critical two-tail	2.2622		2.2622	

4.6 Impacts on Mobility Measures

The mobility measures used in the evaluation include stopped delay, the number of stops, the approach delay, queue length, and the number of queue-stops. The mobility evaluation of the proposed strategy was conducted for the main street movements, side-street movements, and all movements combined. The mobility assessment of the CV-based RLVW application was done with and without AGP. Without implementing the AGP, the results showed that the RLVW application has no significant impact on the case study intersection delay. Thus, only the impacts of the RLVW with AGP will be presented in this section.

4.6.1 AGP Impacts on Mobility with Moderate Traffic Demands

This section is divided into two sub-sections. Section 4.6.1.1 presents the mobility assessment in terms of stopped delay, the number of stops, and the approach delay. Then, the mobility assessment in terms of the queue length and the number of queue-stops is presented in section 4.6.1.2.

4.6.1.1 Impacts of the AGP on Traffic Delays

Table 4-6 shows the impacts of the AGP on the major street delays with moderate traffic volumes. The results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 21.95 seconds and 23.57 seconds. In addition, the average number of stops per vehicle fluctuates from 0.81 stops per vehicle to 0.84 stops per vehicle. Moreover, the approach delay per vehicle fluctuates between 32.24 seconds to 34.32 seconds.

Table 4-6: Impacts of AGP on the Major Street Delay with Moderate Traffic Demands

RLVW Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	23.06	0.83	33.44
10%	22.92	0.83	33.28
20%	22.62	0.82	32.91
30%	22.05	0.81	32.24
40%	21.95	0.81	32.25
50%	23.26	0.83	33.78
60%	22.59	0.81	33.01
70%	22.68	0.81	33.14
80%	23.56	0.84	34.27
90%	23.57	0.83	34.31
100%	23.52	0.84	34.32

Table 4-7 shows the impacts of the AGP on the side-street delays. The results show that the AGP has no impact on the side-street delay with moderate traffic volumes.

Table 4-7: Impacts of AGP on the Side-street Delay with Moderate Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	16.25	0.67	24.43
10%	16.31	0.67	24.51
20%	16.71	0.67	24.91
30%	16.37	0.67	24.55
40%	16.57	0.67	24.81
50%	16.48	0.67	24.79
60%	16.43	0.67	24.68
70%	16.43	0.67	24.71
80%	16.36	0.67	24.63
90%	16.50	0.67	24.86
100%	16.34	0.67	24.72

For instance, with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 16.25 seconds and 16.71 seconds. In addition, the results show that the average number of stops per vehicle was constant when increasing the CV utilization rate from 0% to 100%. Moreover, the approach delay per vehicle fluctuates between 24.43 seconds to 24.91 seconds indicating no significant changes in delays on the side-street.

Table 4-8 shows the impacts of the AGP on the overall intersection delays with moderate traffic. The results show that the AGP has no significant impact on the overall intersection delay with moderate traffic volumes. For instance, with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 19.37 seconds and 20.16 seconds. In addition, the results show that the average number of stops per vehicle fluctuates between 0.74 stops per vehicle to 0.76 stops per vehicle. Moreover, the approach delay per vehicle fluctuates between 28.61 seconds to 29.84 seconds indicating minor changes in delays.

Table 4-8: Impacts of AGP on the Overall Intersection Delays with Moderate Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	19.85	0.76	29.19
10%	19.81	0.75	29.16
20%	19.83	0.75	29.14
30%	19.37	0.74	28.61
40%	19.40	0.74	28.73
50%	20.06	0.76	29.54
60%	19.69	0.74	29.08
70%	19.73	0.74	29.16
80%	20.16	0.76	29.73
90%	20.22	0.76	29.84
100%	20.13	0.76	29.79

4.6.1.2 Impacts of the AGP on Traffic Queues

Table 4-9 shows the impacts of the AGP on the traffic queues for each movement when increasing the RLVW utilization rate from 0% to 100% with moderate traffic.

Table 4-9: Impacts of AGP on the Traffic Queues with Moderate Traffic and Different Utilization Rates (UR)

	UR 0%		UR 10%		UR 20%		UR 30%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	11.70	95.6	11.84	95	12.44	98.3	11.35	92
2: SBT	54.43	282	54.96	286.1	55.24	282.5	52.95	278.2
3: EBL	42.20	190.5	41.48	193.4	41.65	194.1	39.82	191.4
4: WBT	86.89	407.4	87.53	408.5	88.05	410.7	89.50	416
5: SBL	11.91	97.1	12.13	98.4	12.52	99.8	12.45	98.4
6: NBT	53.39	281.9	53.16	281.4	53.91	278.8	54.58	281.6
7: WBL	45.68	216.6	43.42	214.2	43.49	213.3	41.97	208.9
8: EBT	91.33	413.8	92.05	410	89.04	405.9	86.30	399.7
	UR 40%		UR 50%		UR 60%		UR 70%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	11.00	90.9	11.46	93.9	11.12	92.6	11.29	91.6
2: SBT	55.44	285.4	55.68	287.2	56.06	285.1	55.46	283
3: EBL	40.13	191.5	40.99	192.5	40.27	190.6	39.50	189.1
4: WBT	88.11	408.5	93.70	420.6	89.92	411.7	88.72	410.5
5: SBL	12.04	96.4	12.13	97.6	12.33	97.4	12.25	99.6
6: NBT	54.82	282.4	53.92	280.3	52.89	275.6	53.24	277.5
7: WBL	42.72	212.8	45.58	219.5	43.58	212.4	44.93	215.2
8: EBT	86.31	403.8	91.82	414.6	89.44	413.7	90.17	410.9
	UR 80%		UR 90%		UR 100%			
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops		
1: NBL	10.87	88.8	11.69	93.9	11.31	91.3		
2: SBT	54.58	281.8	55.25	284.8	55.10	284.2		
3: EBL	40.79	192.8	44.66	199.1	44.62	200.7		
4: WBT	92.17	420.8	89.13	412.8	87.18	404.8		
5: SBL	12.47	98	11.82	95	11.90	94.1		
6: NBT	53.82	278.8	54.67	281.7	54.05	281.5		
7: WBL	46.91	218.9	48.02	221.5	47.33	220.7		
8: EBT	94.26	421.2	89.69	412.3	91.44	414.9		

Figure 4-7 shows the impacts of the AGP on the traffic queues for each movement with increasing the RLVW utilization rate from 0% to 100%. It can be inferred from Figure 4-7 that the AGP has no significant impact on the queue lengths for all movements

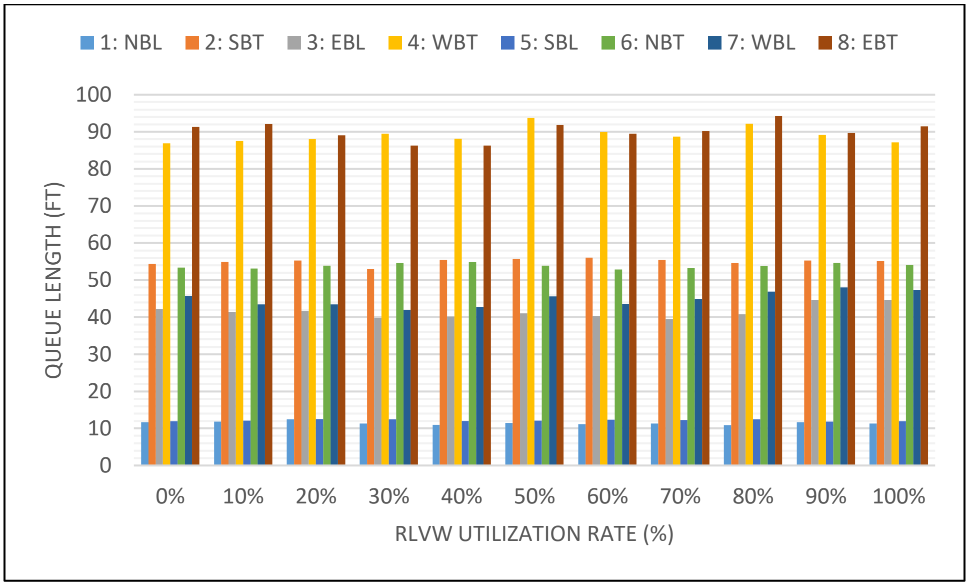

Figure 4-7 Impacts of the AGP on Queue Length with Moderate Traffic Demands

4.6.2 AGP Impacts on Mobility with 10% Increase in Traffic Demands

This section is divided into two sub-sections. Section 4.6.2.1 presents the mobility assessment in terms of stopped delay, the number of stops, and the approach delay. Then, the mobility assessment in terms of the queue length and the number of queue-stops is presented in section 4.6.2.2.

4.6.2.1 Impacts of the AGP on Traffic Delays

Table 4-10 shows the impacts of the AGP on the major street delays with a 10% increase in traffic volumes. The results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 30.35 seconds and 32.38 seconds. In addition, the average number of stops per vehicle fluctuates between 0.97 stops per vehicle to 1.02 stops per vehicle. Moreover, the approach delay per vehicle fluctuates between 42.18 seconds to 44.57 seconds. The results show that the AGP has no significant impact on the major street delay with a 10% increase in traffic volumes.

Table 4-10: Impacts of AGP on the Major Street Delay with a 10% Increase in Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	30.35	0.98	42.18
10%	30.48	0.98	42.39
20%	30.61	0.97	42.50
30%	30.30	0.97	42.18
40%	32.38	0.99	44.57
50%	32.31	1.00	44.54
60%	31.92	0.99	44.16
70%	31.59	0.98	43.81
80%	32.08	1.00	44.44
90%	32.14	1.01	44.57
100%	31.97	1.02	44.54

Table 4-11 shows the impacts of the AGP on the side-street delays. The results show that the AGP has no significant impact on the side-street delay with a 10% increase in traffic volumes. For instance, with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 17.59 seconds and 18.31 seconds. In addition, the results show that the average number of stops per vehicle was constant with increasing the CV utilization rate from 0% to 100%. Moreover, the approach delay per vehicle fluctuates between 26.02 seconds to 26.80 seconds, indicating no significant change in delays on the side-street.

Table 4-11: Impacts of AGP on the Side-street Delay with 10% Increase in Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	18.01	0.69	26.39
10%	17.92	0.69	26.28
20%	17.92	0.69	26.32
30%	17.80	0.68	26.15
40%	18.31	0.69	26.80
50%	18.26	0.69	26.80
60%	18.09	0.69	26.60
70%	17.82	0.69	26.29
80%	17.59	0.69	26.02
90%	17.70	0.69	26.22
100%	18.13	0.69	26.75

Table 4-12 shows the impacts of the AGP on the overall intersection delays. With a 10% increase in volumes, the AGP has no significant impact on the overall intersection. For instance, with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 24.52 seconds and 25.70 seconds.

Table 4-12: Impacts of AGP on the Overall Intersection Delays with a 10% Increase in Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	24.52	0.85	34.72
10%	24.54	0.84	34.78
20%	24.60	0.84	34.83
30%	24.37	0.83	34.57
40%	25.70	0.85	36.14
50%	25.67	0.86	36.16
60%	25.35	0.85	35.81
70%	25.09	0.84	35.54
80%	25.23	0.85	35.74
90%	25.32	0.85	35.90
100%	25.42	0.86	36.12

In addition, the results show that the average number of stops per vehicle fluctuates between 0.83 stops per vehicle to 0.86 stops per vehicle. The approach delay per vehicle fluctuates between 34.57 seconds to 36.16 seconds indicating minor changes in delays.

4.6.2.2 Impacts of the AGP on Traffic Queues

Table 4-13 shows the impacts of the AGP on the traffic queues for each movement with increasing the RLVW utilization rate from 0% to 100%. The queue length is specified in terms of unit length (feet).

Table 4-13: Impacts of AGP on the Traffic Queues with a 10% Increase in Traffic Demands and Different Utilization Rates (UR)

	UR 0%		UR 10%		UR 20%		UR 30%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	13.28	103	13.33	101.7	13.42	103.2	12.77	99.5
2: SBT	68.71	324.9	66.69	316.9	67.21	320.9	66.50	318.9
3: EBL	55.02	223.5	52.58	225.6	52.69	225.7	52.00	225.4
4: WBT	143.92	538.3	137.29	520.9	149.91	538.7	152.57	545
5: SBL	14.61	108.4	14.88	111.4	14.89	109	14.58	107.4
6: NBT	66.08	314.2	66.68	317.9	65.99	313.9	66.40	314.6
7: WBL	60.21	254	60.29	252.9	59.54	251.9	60.90	252.4
8: EBT	149.32	539.2	159.02	552.9	152.34	544.7	145.23	537.6
	UR 40%		UR 50%		UR 60%		UR 70%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	13.46	103.6	13.68	105.8	12.92	100.7	12.47	99.2
2: SBT	69.67	325.6	70.69	328.9	67.89	322.7	67.10	320.4
3: EBL	52.69	220.6	54.12	226.3	53.34	225.6	52.71	225.6
4: WBT	158.61	559.3	155.94	554.4	153.19	554.7	156.01	555.2
5: SBL	14.82	110.5	14.55	109.1	15.29	109.9	14.73	110.7
6: NBT	67.14	316.1	66.11	314.2	66.79	316.4	65.91	313.9
7: WBL	61.02	255.1	60.45	256	61.19	255.7	59.59	251
8: EBT	170.17	568.4	168.43	564.9	164.68	563.3	161.94	555.7

	UR 80%		UR 90%		UR 100%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	12.43	97.3	12.54	97.3	13.30	101.8
2: SBT	65.99	320.4	66.33	319.1	69.13	322.3
3: EBL	53.71	226.3	56.22	232.1	56.98	229.4
4: WBT	154.68	552.4	151.76	549.5	150.67	551.8
5: SBL	14.23	107.8	14.74	109.7	14.74	109.5
6: NBT	65.58	312.4	66.55	316.5	66.89	318.5
7: WBL	63.54	260.2	63.05	261.1	62.20	260
8: EBT	163.75	558.9	161.89	557.7	163.91	565.7

Figure 4-8 shows the impacts of the AGP on the traffic queues for each movement with increasing the RLVW utilization rate from 0% to 100%. It can be inferred from Figure 4-8 that the AGP has no significant impact on the queue lengths for all movements

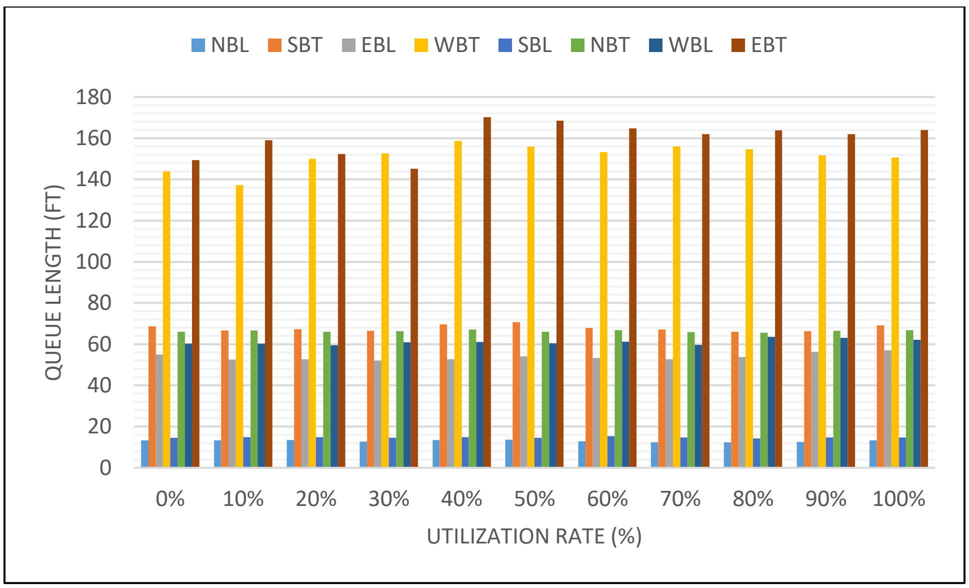

Figure 4-8 Impacts of the AGP on Queue Length with a 10% Increase in Traffic

4.6.3 AGP Mobility Impacts with 20% Increase in Traffic Demands

This section is divided into two sub-sections. Section 4.6.3.1 presents the mobility assessment in terms of stopped delay, the number of stops, and the approach delay. Then, the mobility assessment in terms of the queue length and the number of queue-stops is presented in section 4.6.3.2.

4.6.3.1 Impacts of the AGP on Traffic Delays

Table 4-14 shows the impacts of the AGP on the major street delays with a 20% increase in traffic volumes. The results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle increased from 45.33 seconds with 0% CV to 53.38 seconds (an increase of 17.75%) with 100% CV. In addition, the average number of stops per vehicle increased from 1.27 stops per vehicle to 1.38 stops per vehicle (an increase of 8.66%). Moreover, the approach delay per vehicle increased from 60.33 seconds with 0% CV to 69.25 seconds (an increase of 14.78%) with 100% CV. The results show that the AGP can potentially increase the major street stopped delay and approach delay in the case of increasing the traffic volumes by 20%.

Table 4-14: Impacts of AGP on the Major Street Delay with 20% Increase in Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	45.33	1.32	60.33
10%	50.09	1.32	64.74
20%	50.40	1.35	64.71
30%	50.96	1.34	66.29
40%	51.00	1.34	65.24
50%	51.00	1.34	65.50
60%	51.35	1.35	66.73
70%	51.14	1.35	66.55
80%	51.42	1.35	66.98
90%	52.46	1.37	68.15
100%	53.38	1.38	69.25

Table 4-15 shows the impacts of the AGP on the side-street delays with a 20% increase in traffic volumes. The results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle increased from 15.90 seconds with 0% CV to 20.99 seconds (an increase of 32.01%) with 100% CV. However, the average number of stops per vehicle was almost constant when the CV utilization rate increased from 0% to 100%. Moreover, the approach delay per vehicle increased from 25.10 seconds with 0% CV to 31.49 seconds (an increase of 25.45%) with 100% CV. The results show that the AGP can potentially increase the side-street stopped delay and approach delay in the case of increasing the traffic volumes by 20%.

Table 4-15: Impacts of AGP on the Side-street Delay with 20% Increase in Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	15.90	0.72	25.10
10%	16.93	0.71	27.78
20%	18.95	0.71	27.82
30%	19.30	0.71	27.91
40%	19.44	0.71	28.05
50%	19.49	0.71	28.15
60%	19.49	0.71	28.17
70%	19.76	0.72	28.53
80%	20.26	0.72	29.80
90%	20.38	0.72	30.02
100%	20.99	0.71	31.49

Table 4-16 shows the impacts of the AGP on the overall intersection delays. The results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle increased from 30.07 seconds with 0% CV to 38.26 seconds (an increase of 27.24%) with 100% CV. However, the average number of stops per vehicle was almost constant when the CV utilization rate increased from 0% to 100%. Moreover, the approach delay per vehicle increased from 47.00 seconds with 0% CV to 49.77 seconds (an increase of 6%) with 100% CV. The results show that the AGP can potentially increase the overall intersection stopped delay and approach delay in the case of increasing the traffic volumes by 20%. This increase in delay is directly attributable to the provision of AGP, as calculated in this study, and the assignment of additional green to the RLVW detected vehicles on the through movements of the main street.

Table 4-16: Impacts of AGP on the Overall Intersection Delays with a 20% Increase in Traffic Demands

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)
0%	30.07	1.04	47.00
10%	32.43	1.04	47.45
20%	33.56	1.05	47.64
30%	35.90	1.04	48.04
40%	35.28	1.03	47.29
50%	35.28	1.03	47.30
60%	36.15	1.04	48.34
70%	36.22	1.05	48.47
80%	36.27	1.05	48.60
90%	37.87	1.06	49.30
100%	38.26	1.06	49.77

4.6.3.2 Impacts of the AGP on Traffic Queues

Table 4-17 shows the impacts of the AGP on the traffic queues for each movement with increasing the RLVW utilization rate from 0% to 100%.

Table 4-17: Impacts of AGP on the Traffic Queues with a 20% Increase in Traffic Demands and Different Utilization Rates (UR)

	UR 0%		UR 10%		UR 20%		UR 30%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	15.62	111.9	15.43	113	15.27	112.7	15.39	113.3
2: SBT	80.43	353.2	79.24	354.2	79.01	353.8	80.51	358.9
3: EBL	75.98	262.8	73.09	263.8	74.63	269.3	75.57	269.4
4: WBT	257.57	716.5	285.18	757.4	294.14	772.5	301.82	782.7
5: SBL	15.97	115.2	16.08	115.4	16.09	117	16.15	117.5
6: NBT	81.51	360.8	82.34	365.5	83.04	367.5	82.06	365.7
7: WBL	81.50	305.6	82.49	305.1	79.41	300.5	77.89	295.9
8: EBT	332.10	819.2	328.91	806.7	329.93	820.3	332.69	823.8

	UR 40%		UR 50%		UR 60%		UR 70%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	15.64	113.3	15.71	112.5	15.57	112.5	16.00	113.3
2: SBT	83.45	359.4	83.50	361.9	83.53	362.8	83.96	363.3
3: EBL	74.33	267.2	73.24	268.5	75.08	269.9	71.64	264.9
4: WBT	281.15	757.3	285.43	760.1	287.37	767.6	279.56	752
5: SBL	15.42	114.9	16.24	115	16.13	116.7	16.28	116.8
6: NBT	80.75	362.9	80.38	360.9	80.87	359.8	82.41	364.6
7: WBL	78.51	297.7	80.44	304.6	84.81	309.8	82.82	305
8: EBT	324.41	807	318.52	792.3	333.01	811.7	343.32	824.2

	UR 80%		UR 90%		UR 100%	
Queue Counter	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops	Queue Length (ft)	Queue Stops
1: NBL	15.63	113.8	15.51	111.5	15.58	110.7
2: SBT	84.07	362.9	84.52	366.6	80.66	354.3
3: EBL	71.41	264.1	80.54	273.9	77.47	267.8
4: WBT	289.00	768.6	281.55	760.5	277.24	748.6
5: SBL	15.91	117.1	15.91	116.8	16.17	116.8
6: NBT	82.69	364.6	83.37	362.9	83.89	365.5
7: WBL	82.39	307.1	85.11	311	86.31	313.4
8: EBT	339.21	810.5	346.25	824.9	363.62	847.3

Figure 4-9 shows the impacts of the AGP on the traffic queues for each movement with increasing the RLVW utilization rate from 0% to 100%. It can be inferred from Figure 4-9 that the AGP has no significant impact on the queue lengths for all movements

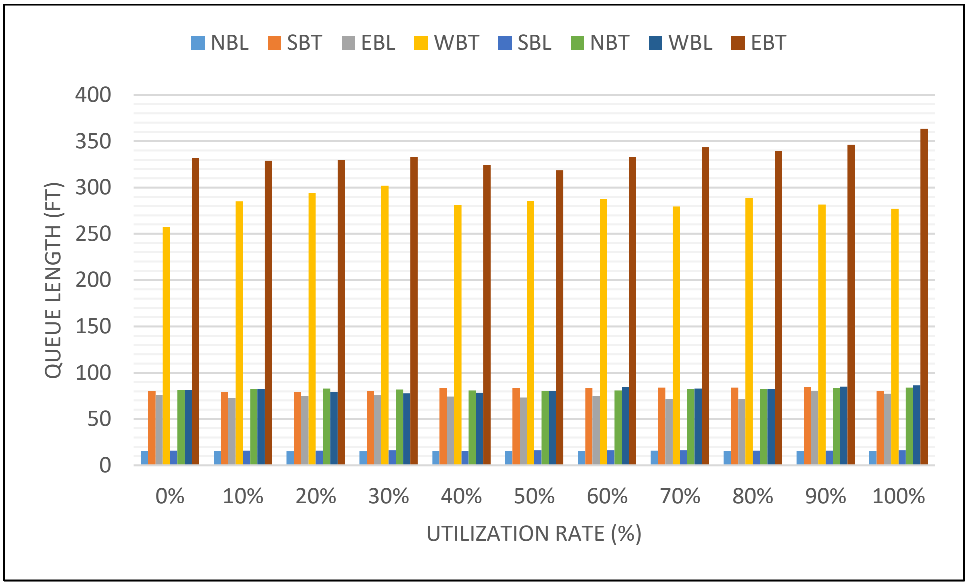

Figure 4-9 Impacts of the AGP on Queue Length with a 20% Increase in Traffic

4.7 Performance Evaluation of RLVW under Coordinated Intersections

In order to understand the impacts of signal coordination on the performance of the RLVW application, two basic four-leg signalized intersections were modeled as shown in Figure 4-10. Similar to modeling the RLVW in an isolated intersection, the parameters needed to estimate the AGP in coordinated intersections are the approach speed, the stopping distance, and the time required to clear the intersection. The utilized approach speed in the calculation of the AGP is the 85th percentile speed, as discussed in the Connected Intersection effort funded by the USDOT mentioned earlier. As shown in Figure 4-10, the RLVW detection zone is an area on a through movement lane where the vehicle is to be detected by the RSE through vehicle-to-infrastructure communication to support the RLVW application. The detection zone location is set such that the distance from the stop line to the RLVW detection zone is equal to a full stopping distance. If the CI detects a vehicle in the RLVW detection zone, the associated movement is in green, and the signal controller is not terminating the movement, then the controller needs to set the minimum end time of the movement phase to the current time plus the AGP. If the CI determines that a movement currently in green is to terminate, the controller provides an AGET that is equal to or greater than the minimum end time of the phase. The controller provision of the AGET allows the RLVW application on the OBE to receive accurate SPaT messages. Vehicles upstream of the detection zone will have enough time to stop before the stop line. The assessment is done based on mobility and safety performance measures outlined earlier. The mobility measures are the stopped delay and number of stops based on simulation model outputs. The safety measures involve collecting the total number of RLR events. The ideal offset for the modeled signalized intersections is equal to 10.8 seconds. Therefore, the results were collected for two different coordination scenarios; a) Coordination with zero-seconds offset and b) Coordination with 11-seconds offset.

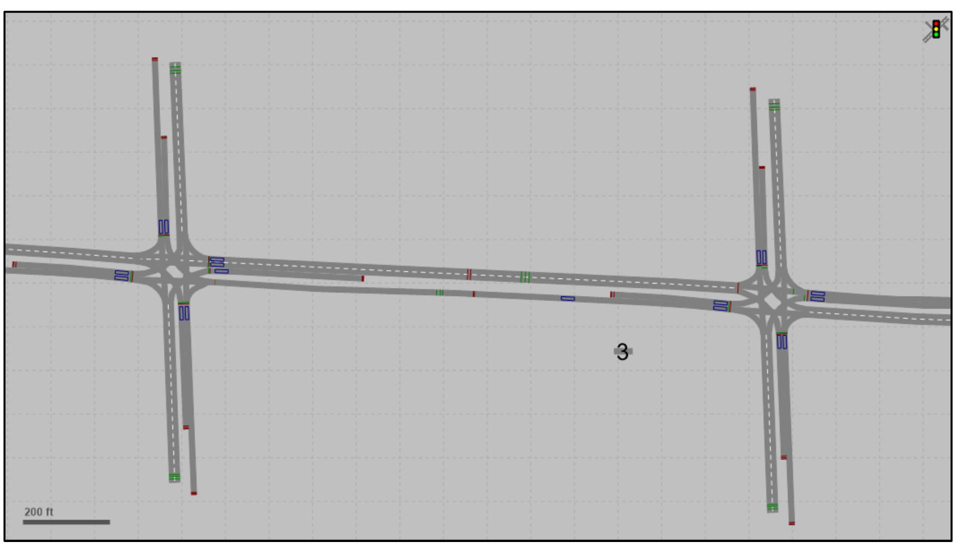

Figure 4-10 Case Study Coordinated Signalized Intersections

4.7.1 Arrivals-on-Green for the Two Modeled Coordination Scenarios

The analysis started with collecting the total number of vehicles arriving on green for a total of 43 cycles. A data collection point was placed upstream of the signalized intersection to capture the number of vehicles arriving on the green. Figure 4-11 shows the arrivals-on-green for the two modeled scenarios mentioned earlier.

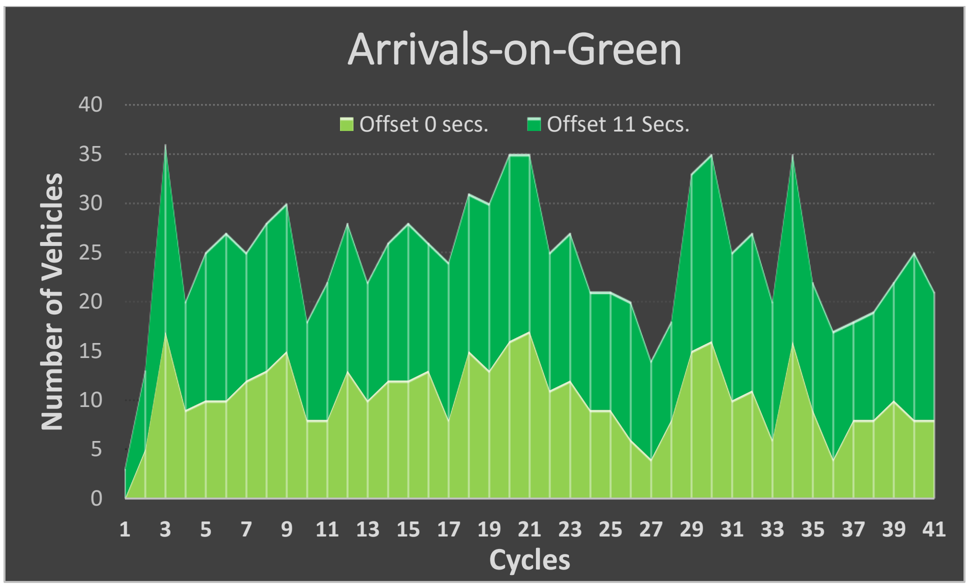

Figure 4-11 Vehicle Arrivals-on-Green

It can be inferred Figure 4-11 that the total number of vehicles arriving on green increased significantly from scenario (a) to scenario (b). The average number of vehicles arriving on green for the total 43 cycles increased by 36.25%.

4.7.2 Performance Measures for CV-Based RLVW for the Two Modeled Scenarios without the Provision of AGP

The mobility measures used in the evaluation include stopped delay, the average number of stops, and approach delay. First, in the case of coordination with zero offset and without AGP, the results in Table 4-18 show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 24.21 seconds and 25.71

seconds. In addition, the average number of stops per vehicle fluctuates between 0.72 stops per vehicle and 0.82 stops per vehicle. However, the approach delay increased from 31.80 seconds with a 0% CV utilization rate to 36.10 seconds with a 100% CV utilization rate (an increase of 14.46%). The results show that in the case of coordination with zero offset and without AGP, the CV-based RLVW application has no significant impact on the stopped delay and the average number of stops, however, the approach delay increased by 14.46%.

Table 4-18: Modeled Signalized Intersections with Zero-Seconds Offset

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)	RLR
0%	24.21	0.72	31.80	11
10%	24.73	0.78	32.97	9
20%	24.23	0.79	32.80	6
30%	24.79	0.82	33.71	8
40%	24.62	0.80	33.79	11
50%	25.36	0.81	34.97	10
60%	25.09	0.79	34.92	7
70%	25.46	0.81	35.74	5
80%	24.96	0.79	35.39	7
90%	25.71	0.78	36.43	5
100%	25.51	0.76	36.40	7

The utilized safety performance measure is the total number of red-light running events. First, in the case of coordination with zero offset and without AGP, the results in Table 4-18 show that the RLR fluctuates between 5 and 11 events per hour. As previously mentioned, the reason for this fluctuation is the uncertainty of the end-of-green intervals of the actuated phases.

In the case of coordinated operation with 11-seconds offset and without AGP, the results in Table 4-19 show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay increased from 23.00 seconds with 0% CV utilization rate to 25.09 seconds with 100% CV utilization rate (an increase of 9.08%). In addition, the average number of stops per vehicle fluctuates between 0.70 stops per vehicle and 0.81 stops per vehicle. Moreover, the approach delay increased from 30.58 seconds with 0% CV utilization rate to 36.12 seconds with 100% CV utilization rate (an increase of 18.12%)

Table 4-19: Modeled Signalized Intersections with 11-Seconds Offset

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)	RLR
0%	23.00	0.70	30.58	11
10%	23.14	0.76	31.24	10
20%	23.50	0.78	32.04	12
30%	23.77	0.80	32.64	11
40%	23.82	0.80	33.01	5
50%	24.34	0.81	33.96	6
60%	24.35	0.80	34.26	6
70%	25.07	0.81	35.33	7
80%	25.07	0.79	35.76	6
90%	25.06	0.78	35.95	8
100%	25.09	0.75	36.12	7

Regarding the safety performance measure, in the case of coordination with 11-seconds offset and without AGP, the results in Table 4-19 show that the RLR fluctuates between 5 and 12 events per hour.

4.7.3 Performance Measures for CV-Based RLVW for the Two Modeled Scenarios with the Provision of AGP

As previously mentioned, the mobility measures used in the evaluation include stopped delay, the average number of stops, and approach delay. First, in the case of coordination with zero offset and with AGP, the results in Table 4-20 show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between

26.48 seconds and 27.81seconds. In addition, the average number of stops per vehicle fluctuates between 0.92 stops per vehicle and 0.94 stops per vehicle. Moreover, the approach delay fluctuates between 37.29 seconds and 39.10 seconds. The results show that in the case of coordination with zero offset and with AGP, the CV-based RLVW application has no significant impact on the intersection delay.

Table 4-20: Modeled Signalized Intersections with Zero-Seconds Offset

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)	RLR
0%	26.48	0.92	37.29	17.2
10%	26.58	0.93	37.49	15.7
20%	26.57	0.92	37.50	14
30%	27.09	0.93	38.09	12.3
40%	26.88	0.94	38.89	10.5
50%	27.09	0.92	37.95	9.8
60%	27.37	0.93	38.52	7.1
70%	26.98	0.92	38.09	4.9
80%	27.40	0.93	38.55	4.2
90%	27.59	0.94	39.10	4.4
100%	27.81	0.94	38.93	4.3

The utilized safety performance measure is the total number of red-light running events. First, in the case of coordination with zero offset and with AGP, the results in Table 4-20 show a clear decreasing trend in the average number of RLR from 17.2 events per hour to 4.3 events per hour.

In the case of coordinated operation with 11-seconds offset and with AGP, the results in Table 4-21 show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per increased from 17.89 seconds with 0% CV utilization rate to 19.83 seconds with 100% CV utilization rate (an increase of 10.84%). In addition, the average number of stops per vehicle fluctuates between 0.69 stops per vehicle and 0.76 stops per vehicle. Moreover, the approach delay fluctuates between 30.56 seconds and 32.60 seconds.

Table 4-21: Modeled Signalized Intersections with 11-Seconds Offset

CV Utilization Rate (%)	Stopped Delay (sec/veh)	Average Number of Stops per vehicle	Approach Delay (sec/veh)	RLR
0%	17.89	0.71	30.56	13.2
10%	17.92	0.74	32.16	9.8
20%	18.00	0.70	30.58	9.5
30%	18.10	0.74	32.65	8.7
40%	18.40	0.72	31.16	7.3
50%	18.43	0.75	32.31	5.9
60%	19.29	0.69	30.37	5.2
70%	19.30	0.73	32.60	5.4
80%	19.65	0.73	32.40	4
90%	19.75	0.69	30.57	3.5
100%	19.83	0.76	31.58	3.2

Regarding the safety performance measure, in the case of coordination with 11-seconds offset and with AGP, the results in Table 4-21 show a clear decreasing trend in the number of RLR fluctuates from 13.2 events per four to 3.2 events per hour.

In comparing the results with and without the provision of AGP, it can be concluded that the AGP can improve the safety benefits of the CV-based RLVW application under coordinated-actuated signalized intersections without compromising the intersection delay.

4.8 Summary

The application of the methodology presented in this chapter shows that in the case of pre-timed signal control, there are small differences in the assessed performance when using the EILS, SILS, and HILS platforms. In the case of actuated control, the study results showed significant differences in the assessed performance when using the EILS compared to the use of the other two platforms. The SILS and the HILS produced similar results.

The results showed that the actuated signal controller can have a significant impact on the performance of the CV-based RLVW application at signalized intersections. With actuated traffic signal operations, there is uncertainty in the end-of-green information provided to the vehicles using CV messages. This is uncertainty is because the RLVW algorithm lacks accurate input information about when exactly the phase is going to be terminated since this termination occurs when a gap of a particular length is encountered at the detector. This chapter introduced and evaluated a concept recently proposed in a national effort to provide an AGP, which is a definitive time when the green interval will end to mitigate the uncertainties associated with the green termination and to improve the performance of the CV application.

In summary, the results showed that, with semi-actuated control, the safety benefits of the RLVW without the use of AGP were limited. On the other hand, the study results show that by introducing the AGP, the RLVW can reduce the number of red-light running events at signalized intersections by approximately 92% with RLVW utilization of 100%. However, the results show that the application of the AGP, as applied and assessed in this dissertation, can have increased stopped delay, number of stops, and approach delay during congested traffic conditions.

CHAPTER 5
CONCLUSIONS

This study investigated the performance of the RLVW, as an example of CV-based applications under pre-timed signal control and semi-actuated signal control utilizing EILS, SILS, and HILS platforms. The study assessed the performance of the RLVW under the three platforms. In addition, the study evaluates the challenges associated with the uncertainty of the end-of-green time provided by actuated signal controllers on the performance of the RLVW application. Furthermore, this study investigated a method recently proposed in a national effort to provide an AGP to extend the green time to mitigate the uncertainties associated with the green termination and to improve the performance of the CV application. This chapter summarizes the findings of this research and outlines the precincts for future research.

5.1 Summary and Conclusions

This study shows that the calibration of the probability of stopping in the microscopic simulation tool is an essential stage for the simulation of the RLVW application. The sensitivity analysis of the impacts of the values of the three coefficients of calibration showed that the α parameter had a minor effect on the Stop or Go decisions and RLR events in the simulation. However, the $\beta 1$ and $\beta 2$ were positively correlated with the number of stop-decisions and negatively correlated with the number of go-decisions. Moreover, $\beta 1$ and $\beta 2$ were negatively correlated with the number of RLR violations.

In comparing the RLVW performance using the EILS, SILS, and HILS platforms, the study results showed that in the case of pre-timed signal control, there are small differences in the assessed performance when using the three simulation platforms. In the case of semi-actuated control, the study results showed significantly higher differences in the assessed performance when using the EILS compared to the use of the other two platforms. The SILS and the HILS produced similar results. The differences can be attributed to the variations in the communication latencies between the EILS and the other two simulation platforms.

In comparing the impact of the pre-timed signal control and the semi-actuated signal control on the assessed RLVW operation, the results showed that for pre-timed signal operation, the utilized simulation platform does not have a significant impact on the modeled CV-based RLVW application. However, in the case of semi-actuated signal control operation, the SILS and HILS platforms provided a higher number of red-light running events, right-angle conflicts, and rear-end conflicts compared to the EILS and this is because the number of phase occurrences in the SILS and the HILS is higher than the EILS, which increase the probability of having higher numbers of RLR violations. The simulation results show that the RLVW application was able to successfully reduce the RLR events by approximately 90% by increasing the CV utilization rate from 0% to 100% in the case of pre-timed signal control. However, in the case of semi-actuated signal control, the RLVW algorithm was able to reduce the RLR events by only 26.7% according to the EILS, 15% according to the SILS, and 12.5% according to the HILS with increasing the CV utilization rate from 0% to 100%. The reason for the deterioration in the performance of the RLVW with semi-actuated control is the uncertainty in the end-of-green intervals provided to the vehicles using the SPaT messages since the end-of-green depends on the actuation of the conflicting movements. The study investigated the provision of AGP, as a solution to mitigate this uncertainty.

By comparing the total number of RLR with and without applying the AGP for the case study intersection utilized in this dissertation, the results show that, with moderate traffic demands, the total number of RLR decreased from 8.0 to 5.8 events per hour when the RLVW utilization rate increased from 0% to 100% providing only a 27% improvement in safety. The decrease in the RLR with the utilization rate increase was not continuous and fluctuated as the rate increased. On the other hand, the results of applying the AGP show a clear decreasing trend in the number of RLR events. The total number of RLR decreased from 8.3 to 0.7 events per hour with increasing the CV utilization rate from 0% to 100%. It can be concluded that the AGP is able to improve the performance of the RLVW application under semi-actuated signal control and reduce the red-light running events by approximately 92%.

In the case of a 10% increase in traffic demands, the results show that without utilizing the AGP, the total number of RLR fluctuates between 9.7 to 2.9 events per hour when the RLVW utilization rate increases from 0% to 100%. Although the decrease in the RLR with the increase in the utilization rate was not continuous, the trend was less fluctuated compared to the results in the scenario with moderate traffic demands. On the other hand, the results of applying the AGP show a clear decreasing trend in the number of RLR events. The total number of RLR decreased from 8.7 to 2.2 events per hour with increasing the CV utilization rate from 0% to 100%.

In the case of a 20% increase in traffic demands, the results show that without utilizing the AGP, there is a clear decreasing trend in the total number of RLR between 8.7 to 1.6 events per hour when the RLVW utilization rate increased from 0% to 100%. The decrease in the RLR was more continuous with the increased utilization rate compared to the previous scenarios with moderate traffic demands and a 10% increase in traffic demands. On the other hand, the results of applying the AGP show a similar decreasing trend in the number of RLR events compared to the previous scenarios with moderate traffic demands and 10% increase in traffic demands. The total number of RLR decreased from 8.5 to 1.3 events per hour with increasing the CV utilization rate from 0% to 100%. It can be concluded that the RLVW application was able to provide fewer false alarms due to the uncertainties in the end-of-green intervals with increasing the traffic demand by 10% and 20% compared to the moderate traffic scenario.

The mobility assessment of the CV-based RLVW application was done with and without AGP. Without implementing the AGP, the results showed that the RLVW application has no significant impact on the case study intersection delay. In the case of moderate traffic demands, the results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 21.95 seconds and 23.57 seconds. In addition, the average number of stops per vehicle fluctuates from 0.81 stops per vehicle to 0.84 stops per vehicle. Moreover, the approach delay per vehicle fluctuates between 32.24 seconds to 34.32 seconds. In addition, the results show that the AGP has no impact on the side-street delay with moderate traffic volumes. Moreover, the results show that the AGP has no significant impact on the overall intersection delay with moderate traffic volumes.

In the case of a 10% increase in traffic demands, the results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle fluctuates between 30.35 seconds and 32.38 seconds. In addition, the average number of stops per vehicle fluctuates between 0.97 stops per vehicle to 1.02 stops per vehicle.

Moreover, the approach delay per vehicle fluctuates between 42.18 seconds to 44.57 seconds. It can be concluded that the AGP has no significant impact on the major street delay with a 10% increase in traffic volumes. In addition, the results show that the AGP has no significant impact on the side-street delay with a 10% increase in traffic volumes. Moreover, the results show that the AGP has no significant impact on the overall intersection delay with moderate traffic volumes.

In the case of a 20% increase in traffic demands, the results show that with increasing the CV utilization rate from 0% to 100%, the average stopped delay per vehicle increased from 45.33 seconds with 0% CV to 53.38 seconds (an increase of 17.75%) with 100% CV. In addition, the average number of stops per vehicle increased from 1.27 stops per vehicle to 1.38 stops per vehicle (an increase of 8.66%). Moreover, the approach delay per vehicle increased from 60.33 seconds with 0% CV to 69.25 seconds (an increase of 14.78%) with 100% CV. It can be concluded that the AGP can potentially increase the major street stopped delay and approach delay in the case of increasing the traffic volumes by 20%. In addition, the results show that the AGP can potentially increase the side-street stopped delay and approach delay in the case of increasing the traffic volumes by 20%.

Based on the analysis in this study, it can be concluded that the AGP can improve the performance of the CV-based RLVW application. The combination of the CV-based RLVW application on the on-board equipment and the AGP on the actuated controller can reduce the overall intersection RLR by approximately 92% and improve the overall safety of the signalized intersection as measured by the RLR events, rear-end conflicts, and right-angle conflicts. However, the results showed that the application of the AGP, as applied and assessed in this study, can increase stopped delay, number of stops, and approach delay during congested traffic conditions.

5.2 Research Contributions

This research has identified the challenges and constraints associated with actuated signal controllers when testing and evaluating the performance of RLVW applications as an example of CV-based V2I applications. The research also identified a method to mitigate the challenges and a simulation-based method to assess the impact of RLVW with and without the use of the method. This simulation-based method utilizes a HILS platform developed in this study. A case study was developed to simulate the CV-based RLVW under pre-timed and semi-actuated signal control using the HILS platform.

An important focus of this dissertation is the evaluation of the impacts of the RLVW application under semi-actuated signal operation based on delay and safety performance measures. The research presented a step-by-step methodology for VISSIM simulation model calibration and validation of the RLVW application. Then, the impacts of the RLVW application on mobility and safety at the case study signalized intersection were discussed in detail.

A major contribution of this research is the development of the middleware and its use for building the HILS testing architecture. The developed middleware in this study was based on the NTCIP communication standards and consisted of two main programs. The first program is called BAA_HITL and was developed in a previous Federal Highway Administration (FHWA) project (Ma et al., 2018). The second program is developed as part of this dissertation work, which is called FIU_HILS. This study integrated both programs in one compiled solution module using the C# programming language.

The developed HILS platform is also capable of modeling all types of V2I CV-based applications. The HILS can be used to test the functionality and performance of various applications supported by the Road-side Equipment (RSE), On-board Equipment (OBE), and signal controller vendors. The latest generation of commercially available RSE and OBE promises a robust and reliable connected vehicle to infrastructure wireless communications that can be utilized to enhance the mobility and safety of the transportation system. With the newly added capability of the Connected Vehicle-to-Everything (CV2X) communications module and software, RSUs and OBUs support the accurate exchange of information delivery and the needed functionality of CV-based applications. The Society of Automotive Engineers (SAE) governs the standards for the CV messages format and structure, as part of the SAE J2735 message set dictionary. The developed HILS platform in this dissertation can be used to develop methods to test and evaluate the wireless SAE J2735 messages output from the CV devices of different commercial CV vendors to ensure that these messages as implemented will provide the expected operational performance.

5.3 Recommendations for Future Research

Future studies to extend this dissertation research could include the following:

a. Further investigation is needed to determine the optimal setting of the AGP considering both the mobility and safety impacts.

b. The changes in delay and stops due to the implementation of the AGP are expected to be functions of the demands of various main street and cross street movements. The impacts of different demands on the results could be explored in a future study.

c. Another challenge during the evaluation of CV applications is the difficulty of testing the communication between the different components of the system. For example, the uncertainties associated with the lost communication packages, communication delay, and latencies, among other synchronization challenges. These additional challenges could be explored in future studies.

d. The impact of progression on RLR with and without RLVW can be considered as part of the optimization of signal timing and progression between adjacent intersections.

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JOURNAL PUBLICATIONS

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13. Abaza, O., Arafat, M., & Uddin, M. S. (2020) "Impact of Studded Tire Use on Pavement Structures in Cold Climates" Presented at the 99th TRB Annual Meeting, Washington, DC, January 2020.

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